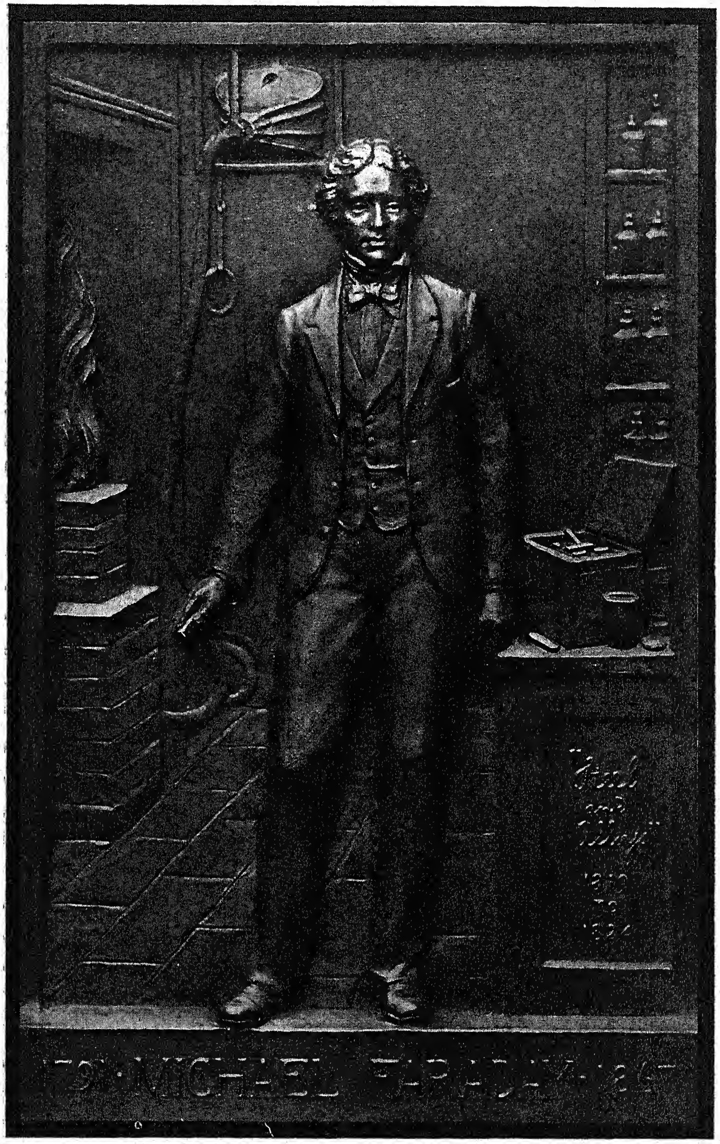

FARADAY IN HIS LABORATORY.

Plaque modelled by F. J. Halnon, R.B.S., and cast in steel.

On the right is shown the box labelled by him in which the 79 specimens of steel were discovered, and on the left the famous "Blast Furnace," in which Faraday made his steel.

[*Frontispiece.*

FARADAY AND HIS METALLURGICAL RESEARCHES

WITH SPECIAL REFERENCE TO THEIR BEARING ON THE DEVELOPMENT OF ALLOY STEELS

BY

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PREFACE

Many books have been written concerning the life and work of Faraday, but none of these has given more than passing mention to his laborious researches concerning the preparation and properties of alloys of steel during the years 1819–1824. The reason for this is not far to seek. Faraday's work in this field was far in advance of the needs of his times. Certain of his alloys were tried on a practical scale, but there was then no general demand for the properties of which alloy steels are capable, and the general state of metallurgical knowledge and practice was such that steelmakers could not readily continue the great work which Faraday had commenced.

From the time when Faraday discontinued his researches until the present time—that is, an interval of some 107 years—no one had, so far as the author is aware, subjected the surviving specimens of his "steel and alloys" to any more than general inspection. Thanks to the kind permission of the Managers of the Royal Institution and the Director of the Science Museum, South Kensington, in regard to the specimens in their charge, the author has been enabled to subject those specimens to full and complete examination and analysis by the resources of a modern research laboratory. The results of that investigation are presented in this volume as a contribution to the history of science and as a tribute to the work and fame of Michael Faraday, probably the greatest experimental investigator the world has ever known.

In the light of his own fifty years of metallurgical experience, largely concerned with alloy steels during the whole of that period, the author claims that the results of the research presented in this book definitely establish that Faraday was the first to engage in systematic research concerning the preparation of alloys of steel.

Also, regarding the matter broadly and without consideration of immediate practical applications, Faraday may justly be called the pioneer of alloy steels. The complete examination of the surviving specimens of his alloys, which has now been made for the first time, shows that they anticipated in a remarkable manner the facts and principles on which the present enormous development of alloy steels is based.

In the course of his investigation of all the circumstances attending Faraday's work on steel and alloys, the author found it necessary to go far and wide in the literature and documents of the past. Many facts of interest emerged and, as far as practicable, these have been embodied in the present work. Nothing in the way of a complete biography has been attempted. That task has already been ably performed by others. The author has, however, traced some of the events of Faraday's earlier years which doubtless attracted him to the research on steel and alloys. Information has been collected, too, in many instances with great difficulty, concerning those with whom Faraday came in contact before and during the period of his steel researches, specially as regards their influence on that work. The state of previous knowledge concerning ferrous metallurgy is reviewed, together with the sequence of events leading up to the "first and most laborious" of Faraday's major researches, that on "steel and alloys," to use his own expression.

The facilities at Faraday's disposal and the methods he employed are fully described, his own words being quoted in many instances in order that the conditions under which he worked may be clearly understood, and an accurate appreciation obtained of his aims and methods. Following this, a detailed account is given of the author's researches on the specimens preserved in Faraday's box at the Royal Institution. In this connection the author is indebted to the Council of the Royal Society for their kind permission to reproduce information first published in his paper, entitled "A Research on Faraday's 'Steel and Alloys'" (*Phil. Trans. A.*,

Vol. 230, September, 1931). A full account is also given of the author's researches on a further group of specimens preserved in the Science Museum, and a number of historic razors of special interest in connection with Faraday's work. In the concluding chapters of the book, the author presents a general appreciation of Faraday's metallurgical researches, and an account of the later developments in alloy steels down to modern times.

It is questionable whether there has ever before been an opportunity of examining in the light of modern knowledge a number of century-old specimens in any way comparable in interest and importance with Faraday's "steel and alloys." The author believes that this sentiment will be generally endorsed, and he offers his heartiest thanks to all those, mentioned more fully in the course of the book, who have assisted him in the laborious but fascinating investigations which the research has involved. His special gratitude, and, indeed, that of the whole world of science, is due to those who granted permission for the specimens to be examined. This broad-minded attitude might well be copied by all who are in charge of relics of the past, for without it the achievements of our predecessors cannot be accurately assessed, and much knowledge may be lost.

ROBERT A. HADFIELD.

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" The metals in use in old times were obtained almost by accident—either pure from the hands of nature or by the rudest and simplest workings.

" But, excited by the result of their labours, and by a rude perception of the important ends to be obtained, men would, in the course of years, not only have their curiosity, but their interest engaged in the pursuit; and, improved by the experience of past ages, we find the alchemists and their followers, in spite of the self-created obscurity which surrounded them, still frequently successful in withdrawing from the concealed stores of nature new metallic wonders, and giving to mankind at one time amusing, at another useful, information.

" As the views of men became clearer, as their growing means continually improved by practice in their hands, new individuals were added to the metallic species, and each addition drew forth applause for the genius of the discoverer, and for his contribution to general chemical science."—FARADAY, in his Sixteenth Lecture on Metals before the City Philosophical Society in 1818.

" Ce n'est pas assez de savoir les principes, il faut savoir MANIPULER." —*Dictionnaire de Trevoux.* From Faraday's *Chemical Manipulation*, 1827.

FARADAY AND HIS METALLURGICAL RESEARCHES

WITH SPECIAL REFERENCE TO THEIR BEARING ON THE DEVELOPMENT OF ALLOY STEELS

CHAPTER I

INTRODUCTION

Faraday, a Great Experimental Philosopher

Undoubtedly Michael Faraday was one of the greatest experimental philosophers the world has ever known. Entirely free from any thoughts of personal gain, and ever seeking truth for truth's sake, he was content with the simplest necessities of life. From early manhood until his closing years, he made one discovery after another, some being of such importance that vast industrial enterprises have since arisen from them. Almost the entire electrical industry of to-day is founded on his discovery of the phenomenon of electromagnetic induction. From the standpoint of its material consequences, this was probably the most important of all Faraday's discoveries. It is certainly the one with which his name is instinctively associated by most people, and the centenary of this discovery has been marked by celebrations on a magnificent scale.

Though the discovery of the action and laws of electromagnetic induction was probably the most important of Faraday's discoveries from the standpoint of modern industry, it must not be forgotten that it was by no means the only remarkable achievement of this great British scientist. If he had made no other discovery, Faraday would still deserve to be remembered as one of the greatest benefactors of the human race, but, on the other hand, if he had never experimented with electricity his name would still be honoured for his chemical discoveries. The truth is that Faraday made many discoveries any one of which would have established his reputation as a distinguished scientist, but so

great is his fame in the electrical field that his other work is apt to receive less than a fair share of appreciation.

This is specially the case where Faraday's metallurgical work is concerned. To many it will come as a surprise to learn that Faraday ever carried out metallurgical researches; in fact, it was his first real research, and occupied a considerable portion of his time and energies during the period 1819 to 1824. Others, acquainted with the bare fact that he investigated "steel and alloys" in his early days, may have subscribed to the words of the biographer who said that these researches "ended in nothing." Any such conclusion can only be based upon a failure to appreciate what Faraday actually accomplished, first in planning his systematic investigation of an extensive series of steel alloys, and then in making such alloys with comparatively primitive resources and practically nothing in the way of earlier knowledge to guide him.

Faraday the Pioneer of Research on Special Steels

It is the object of this book to deal with Faraday's earlier years and his metallurgical researches as fully and thoroughly as possible. This has not been done before, and the work of collecting all the available information has proved to be unexpectedly difficult. At the same time, it has been of fascinating interest both as regards the search for documentary evidence and the complete examination of a large number of specimens of steel and alloys actually made by Faraday himself during the period about 1819–1824. In the course of the investigations it has been necessary to trace the part played by quite a number of persons with whom Faraday came into contact during the early years of the nineteenth century, and this has greatly widened the scope of the work, while adding much to its interest.

After full examination of all the evidence, contemporary and otherwise, and after the most complete investigation of Faraday's specimens, the author has no hesitation in claiming that, although others played their part, Faraday held the centre of the stage throughout these early researches and that Faraday was, in fact, the first to conduct systematic researches on alloy steels.

Faraday's electromagnetic discoveries have largely overshadowed his other work, and this is specially the case so far as his researches on alloy steels are concerned. Yet the author believes that Faraday might be termed the Pioneer of Alloy Steels as justly as he is termed the Father of the Electrical Industry. It was many years before his electrical discoveries were applied on a commercial and industrial basis, and even then this application was made not by

Faraday, but as the result of the labours of many other workers based on the fundamental facts and principles which he had discovered. The situation as regards alloys of steel was very much the same so far as Faraday was concerned. He visualised the possibility of such alloys and foresaw their potentialities. He succeeded in making a large number of new alloys in the face of far greater manipulative difficulties, be it noted, than any he had to overcome in discovering electromagnetic induction.

Faraday was the first to plan and, within the limits of practicability at that time, to carry out an organised research on the manufacture of a series of alloys of steel. Had others been fired by the possibilities of alloy steels as they were by his electrical discoveries, there might well have been a more rapid development than actually occurred.

In fairness to his contemporaries and those who followed immediately after them, it must be admitted that the discovery of a new phenomenon—that of electromagnetic induction—was much more attractive as a subject for further research than the problem of improving a well-known material. Also, cast iron, wrought iron and high carbon steel met all the requirements of those days, and there was certainly no incentive such as exists to-day to meet the demands of engineers for materials with special physical properties. At the same time, it is clear that Faraday realised the desirability of investigating the alloying of steel, and he undoubtedly started in the right direction. If others had followed him promptly we should not have run the risk of forgetting that he was the pioneer.

Faraday's Metallurgical Papers

A classified numerical summary of Faraday's papers, prepared from the Royal Society catalogue of scientific papers, Vol. II., 1868, reveals some interesting facts. Altogether Faraday published 158 papers independently, and four jointly with others. About one-third of these were on electrical subjects, the exact distribution being as follows :—

Electricity	56
Magnetism	17
Chemistry	35
Physics	27
Metallurgy	6
Miscellaneous	21
Total	162

The first of these papers was on the "Analysis of Native Caustic Lime of Tuscany," published in the *Quarterly Journal of Science*, Vol. I., 1816, and the last on "Gas Furnaces," published in the *Proceedings of the Royal Institution*, Vol. III., 1858–1862. By their number, quality and great diversity of subject-matter, these papers are a worthy memorial to their illustrious author. Those in which we are specially interested for the purposes of this book are his metallurgical papers, few in number, but of great interest and a high degree of excellence, considering the state of knowledge at the time when they were written.

Faraday's five papers on ferrous metallurgy were :—

"Separation of Manganese from Iron," *Quarterly Journal of Science*, Vol. VI., 1819.

"An Analysis of Wootz or Indian Steel," *Quarterly Journal of Science*, Vol. VII., 1819.

"Experiments on the Alloys of Steel made with a View to its Improvement," *Quarterly Journal of Science*, Vol. IX., 1820.

"Letter to De La Rive regarding his Steel Experiments," June 26th, 1820, *Bib. Univ. des Sciences*, Vol. XIV., 1820, 205–215.

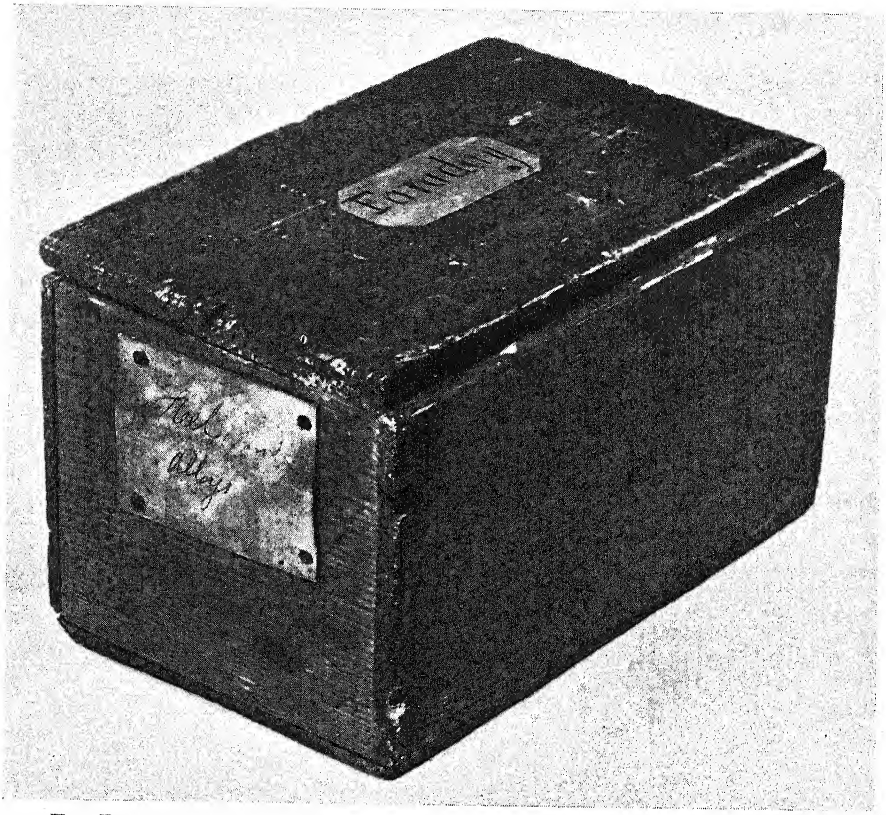
"On the Alloys of Steel," *Phil. Trans.*, Part I., 21–3–1822.

Of these, the third and fifth were in collaboration with James Stodart, while the letter to De La Rive was mainly a summarised account of the researches described in the Royal Institution paper. After the year 1822, there was no metallurgical paper excepting that "On Platinum," presented in 1861 and published in the *R. I. Proc.*, Vol. III.

The two papers on steel alloys, presented to the Royal Institution and the Royal Society respectively, were undoubtedly the most important of Faraday's metallurgical communications. Though for reasons explained later they were published in collaboration with James Stodart, they may fairly be regarded as Faraday's own work so far as the conception and presentation of the research and the preparation of the alloys are concerned.

A full list of the papers on metallurgical subjects by Faraday alone, Stodart alone, and Faraday and Stodart jointly is given in the Appendix. As there shown, Stodart himself wrote four papers between 1802 and 1805, but apart from the joint ones with Faraday, there were no further papers communicated by him to the Royal Institution or the Royal Society relating to metallurgical or other subjects.

It will be seen that Faraday's metallurgical researches were almost exclusively in the ferrous field. Apart from the abovementioned paper on platinum, he delivered the Bakerian Lecture

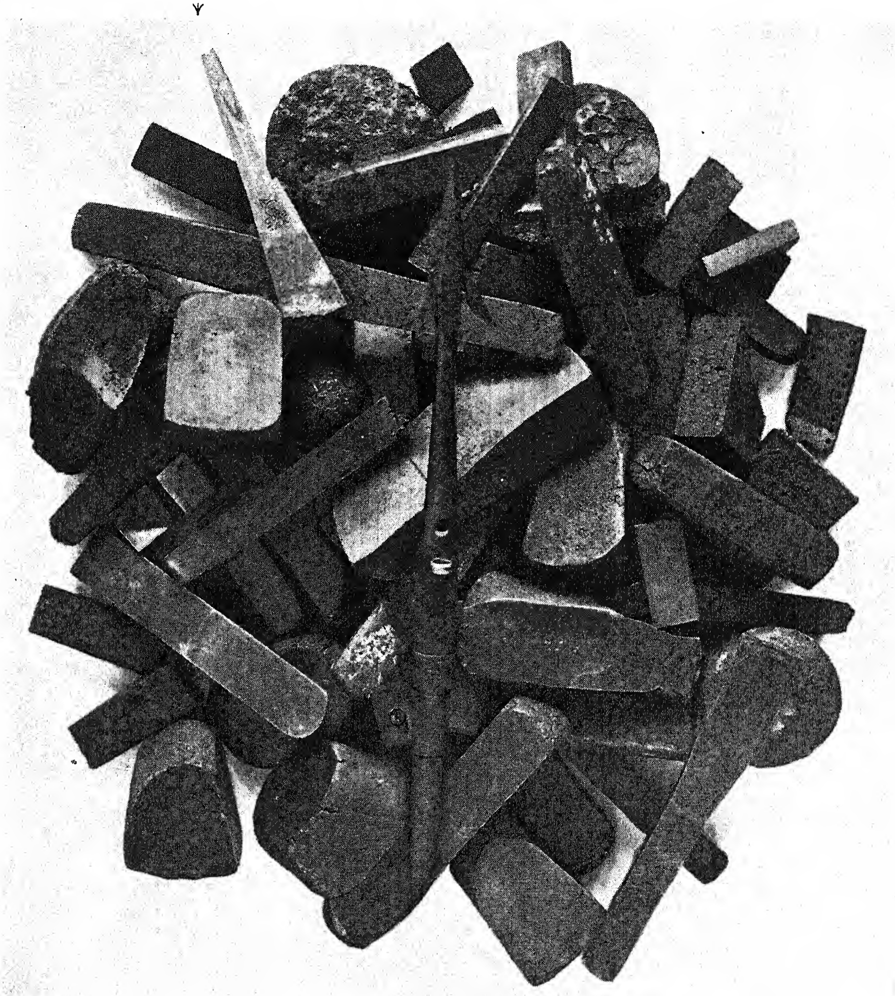


THE DEAL BOX, 9 IN. × $5\frac{1}{2}$ IN. × $5\frac{1}{2}$ IN., IN WHICH THE SPECIMENS OF STEEL WERE FOUND.

The labels on the box are in Faraday's own handwriting.

[*To face p.* 4.

Knife



Two-thirds actual size.

THE 79 STEEL SPECIMENS TAKEN FROM THE BOX SHOWN IN PLATE I.

With regard to the knife in the upper portion of this group marked with Stodart's name, it is interesting to note the zodiacal sign for Iron with the letter P inside Ⓟ♂ indicating the presence of Platinum, as also confirmed by the author's analysis. The sign Ⓡ♂ indicating Rhodium is also shown on the specimen near the small harpoon.

To face p. 5.]

on "Experimental Relations of Gold and other Metals to Light" (*Phil. Trans.*, Vol. 147, 1857), and, strange to say, his last public lecture at the Royal Institution, on June 20th, 1862, had a general bearing on metallurgy, for he then described, and in the most able manner, the regenerative gas furnace introduced and developed by Sir William Siemens, F.R.S. Thus in the latest as well as the earliest days of his active career Faraday was keenly interested in metallurgy and its problems. But for the claims made upon his time and energy by his electrical and other researches he would doubtless have done much more in the metallurgical field. A striking instance of his attitude towards metallurgical investigations and scientific work in general is to be found in a letter which he addressed to Mr. E. Sonstadt on June 27th, 1863, when acknowledging the receipt of some samples of magnesium. In this letter Faraday said: "It is not as yet time to ask after its (magnesium's) probable uses; but we may be allowed to hope for an abundant development of them. What scientific perfection was ever investigated without presenting such uses sooner or later?" Therein lies the spirit of true scientific inquiry; and of alloy steels in particular it may truly be said that no scientific perfection was ever investigated without presenting uses sooner or later.

Faraday's "Steel and Alloys"

This book could not have been written in its present form had it not been possible first to examine thoroughly a large number of the actual specimens made by Michael Faraday himself. In fact, it would hardly have been permissible to put forward the claims which the author makes concerning Faraday's work on steel and alloys unless these claims could be supported by material as well as documentary evidence.

Fortunately, Faraday packed some seventy-nine specimens in a box, which he labelled:

"Steel and Alloys"
"Faraday"

in his own handwriting. There can be no doubt that these specimens were made by Faraday in the Royal Institution building, and there they lay for over a century until, by a happy combination of circumstances, explained in a later chapter, the author was fortunate enough to secure permission to examine the specimens by chemical analysis, physical and mechanical tests and, in fact, by all the resources of a modern research laboratory.

It is the author's object not merely to describe the circumstances

of Faraday's research, the methods and equipment which he used, and the composition and properties of the various steel alloys which have lain almost unnoticed at the Royal Institution since Faraday made them more than a century ago, but also to show that Faraday " builded better than he knew." Altogether some twenty different elements and other substances are mentioned by Faraday in connection with his preparation and examination of steel alloys. This was his first research work of any considerable magnitude, and he was engaged upon it during the years 1819 to 1824 inclusive. Some of his biographers have questioned the value of his metallurgical work, but, writing as a metallurgist himself, and after a most exhaustive examination of Faraday's papers, specimens and other evidence, the author claims that Faraday's work on steel alloys was of the highest order, having regard to all the circumstances. It certainly deserves to rank with his other better-known major researches.

Michael Faraday began the investigation of alloys of steel on a much broader basis than any earlier worker. He was, in fact, the first to conceive and put into effect the idea of a really comprehensive investigation of the possibility of alloying steel with various elements, followed by the examination of the properties of the alloys formed. Some sixty years later it was the author's privilege to start independently on the same line of investigation and, thanks to the better facilities available at the later date and the wider opportunities for using alloy steel once they had been discovered and made, there was no check or hiatus after the author's discovery and invention of manganese steel such as that which followed Faraday's work. The fact remains, however, that full credit is due to Faraday for initiating research on special steels. His " steel alloy sense " was right, as is proved by the remarkable diversity and inestimable importance of the special steels now employed in almost every phase of civilised existence.

CHAPTER II

FARADAY'S RISE TO FAME

THE tale of Faraday's life has often been told, specially as regards the incidents of his career from the time of his first electrical discoveries. Obviously, this is not the place in which to attempt anything in the nature of a fresh complete biography, even were such possible. In the course, however, of his investigation concerning Faraday's work on steel alloys and the circumstances which led to it, the author has come across a great deal of information which may usefully be presented. Much can be learnt from the details of Faraday's earlier years, and much too from the tributes of his friends. By studying these we can learn more of the admirable qualities of Faraday the man, and understand better how he came to work with such patience, industry and success on the intricate problems of steel alloys.

HIS HUMBLE ORIGIN AND ANCESTRY

Faraday was born at Newington Butts, near the Elephant and Castle, London, on September 22nd, 1791, and passed away at Hampton Court on August 25th, 1867. His father, James Faraday, was a smith, and Michael's brother Robert started work as a smith and ended as a gas-fitter. His mother had only a rudimentary education, and was never able to enter into the pursuits of her brilliant son, though she had the greatest pride in his attainments. There was nothing to explain Faraday's genius either by heredity or by the environment of his childhood; in every way it may be said that he "rose from nothing," and his life thus offers much encouragement to others who may start with no special advantages.

There was never any feeling of shame on Faraday's part concerning his humble origin. On the contrary, he remained in continual touch with the less distinguished members of his family throughout his life and, from his own words, it is clear that he retained a special affection for the useful trade of smithing. In 1841, when Faraday's health broke down and he was in Switzerland, he wrote: "Clout-nail making goes on here rather considerably, and is a very neat and pretty operation to observe. I love a smith's shop and anything relating to smithery. My father was a smith." Though

there is no direct evidence on the point, it is within the bounds of possibility that Faraday actually forged the ingots of steel which he made at the Royal Institution into bars. If he did not do so, it would be lack of facilities rather than any lack of interest or manual dexterity that prevented him.

Faraday's father moved to London from Yorkshire shortly after his marriage in 1786, and though Michael was born in London and remained in the Metropolis practically all his life he was a Yorkshireman by descent, and often referred happily to his Yorkshire ancestry. There is no evidence that he ever visited Sheffield, where his larger-sized lots of alloy steels were melted and prepared, and where his "silver steel" and other alloys appear to have found some practical application for a time, but it is interesting to note that he was elected an honorary member of the Sheffield Literary and Philosophical Society on November 1st, 1844, that is, some twenty years after his interest in steel alloys had ceased, and when his reputation as an experimental philosopher had reached its zenith.

Derivation of the Name Faraday.—The author is indebted to Mr. W. Barnard Faraday, the great-nephew of Michael Faraday, for the following information. It appears there are no genealogical records of any certainty earlier than 1708. At that date the name was spelt "ffaraday," and there is a mention in the parish register of Clapham, Yorkshire, of Richard ffaraday, who is described as a stoneman and tiler, and must have held some extent of land in freehold. Probably he was something of a sheep farmer, as the name appears on the Ordnance map of Faraday Ghyl, some way up on the moors towards Bowland Forest. Though known written records go back only to the beginning of the eighteenth century, there is a tradition handed down through various branches of the family that the family or some member of it came to England from Ireland by way of Whitehaven at some time in the fifteenth or sixteenth century. The name "Fereday," or "Farriday," or "Farrady" is not uncommon in Ireland, and the original spelling of "ffaraday" and the constant recurrence of the Christian name Michael lend further support to the tradition of an Irish origin.

It is an interesting fact that the family had a private graveyard of their own on Newby Moor, near Settle, probably owing to their being of the Sandemanian persuasion. The congregation at Kirkby Stephen, of which the grandfather of Michael Faraday was a leading member, was established in 1763, but the graveyard was in the possession of the family before that date.

MICHAEL FARADAY, F.R.S.
1791–1867.

[To face p. 8.

Early Education

From Newington, Michael's father moved to Jacob's Well Mews, Charles Street, Manchester Square, when the boy was five years old, and there the family lived in rooms over a coach house. Little is known concerning the ensuing years of Faraday's youth beyond the fact that they seem to have been spent in the ordinary way common to children who have humble homes and the streets for a playground. Faraday himself said: "My education was of the most ordinary description, consisting of little more than the rudiments of reading, writing and arithmetic at a common day school. My hours out of school were passed at home and in the streets."

At the age of twelve he went as errand boy to Mr. George Ribeau, bookseller and bookbinder, of 2, Blandford Street, near Jacob's Well Mews, and one of his duties was to deliver and collect the newspapers lent out by his master. A year later he was indentured as apprentice to the same worthy man, and served his term of seven years with all distinction as an able and willing worker. Here began his scientific education and, in a letter written to Professor A. A. de la Rive, F.R.S., in 1858, on the death of Mrs. Marcet, he says:

> "Your subject interested me deeply in every way, for Mrs. Marcet was a good friend to me, as she must have been to many of the human race.
>
> "I entered the shop of a bookseller and bookbinder at the age of thirteen in the year 1804, remained there eight years, and during the chief part of the time bound books.
>
> "Now it was in those books in the hours after work that I found the beginning of my philosophy.
>
> "There were two that especially helped me, the *Encyclopædia Britannica*, from which I gained my first notions of electricity, and Mrs. Marcet's *Conversations on Chemistry*, which gave me my foundation on that science."

Here we have a clue to the sources which first directed his attention to electro-chemical investigations. From the *Encyclopædia Britannica* he gained his first notions of electricity, and from *Conversations on Chemistry* his foundation in that science. By the year 1812 he was conducting successful experiments in electrolytic decomposition, using home-made voltaic piles, and writing to his friend Benjamin Abbott on the subject with a remarkably clear appreciation of the phenomena which he had observed and the deductions to be drawn from them.

"Do not fancy," he says, however, in the same letter to de la

Rive, "that I was a profound thinker or a precocious child; I had merely a good deal of life and imagination, and the tales of the Thousand and One Nights pleased me as much as the *Encyclopædia Britannica.* You may therefore easily imagine the pleasure I experienced when I subsequently made the personal acquaintance of Mrs. Marcet, and how delighted I was when my thoughts went backward to contemplate in her at once the past and the present. Whenever I presented her with a copy of my memoirs I took care to add that I sent them to her as a testimony of my gratitude to my first instructress."

"I have the same sentiments towards the memory of your own father," adds Faraday, "for he was, I may say, the first who encouraged and sustained me, first at Geneva, when I had the pleasure of seeing him there,* and afterwards by the correspondence which I regularly maintained with him."

It would be difficult to find a shorter passage which throws more light on Faraday's early education, commencing with the day school and going on through self-tuition by reading and experiment to personal contact with leading scientists of the day.

Beginning of Faraday's Scientific Work

It is evident from his letters to his friend Benjamin Abbott that Faraday conducted many electrical experiments with home-made appliances during the later years of his employment with Mr. Ribeau, the bookbinder. While he was in this service he gained the acquaintance of Mr. Dance, a Member of the Royal Institution, and one of his master's customers. Mr. Dance's sympathy was evidently aroused by Faraday's interest in scientific studies and by the electrical apparatus which he had made, and this led to Mr. Dance taking Faraday to hear some of Davy's lectures at the Royal Institution.

Effect of Davy's Lectures.—This was the turning point in Faraday's career. His enthusiasm fired by the interest and charm of Davy's lectures, the young man wrote out a very full account of four of these lectures, dealing respectively with Radiént (*sic*) Matter, Chlorine, Simple Inflammables, and Metals. His manuscript, consisting of 386 semi-quarto pages, written in his clear strong script, is still in existence at the Royal Institution, and bears the title:

* Faraday here alludes to his Continental tour with Davy. When the travellers stayed with Professor Gaspard de la Rive at Geneva, in 1814, the latter "quickly discerned the merits of the young assistant, and formed relations with him which were interrupted only by death."

FOUR LECTURES
being part of a course on
the elements of
CHEMICAL PHILOSOPHY
delivered by
Sir H. Davy,
LL.D., Sec. R.S.,
F.R.S.E., M.R.I.A., M.R.I., &c. &c.
at the
ROYAL INSTITUTION
and taken off from notes
by
M. Faraday
1812

Faraday was, at this time, twenty-one years of age, and Davy thirty-three years old.

Having completed the transcription of his notes, Faraday submitted them to Davy with a request for employment at the Royal Institution in any capacity connected with science. Davy took counsel with Pepys, one of the founders of the Royal Institution, and himself a scientist. After showing Pepys the letter received from Faraday, the decision Davy arrived at was as follows: "What shall we do with this young man, shall we put him to wash and clean the chemical laboratory glasses and bottles? If he is good for anything he will do this willingly, if he refuses then he is good for nothing." Happily Faraday accepted. In 1813 he began his association with the Royal Institution in this humble capacity, but within a few years he won international recognition as one of the leading chemists of the time.

Continental Tour and Visits

Having been so fortunate as to secure employment in the Royal Institution amidst surroundings and under conditions which offered ideal opportunities for his genius, Faraday was yet more fortunate in having, almost at once, the further advantage of accompanying Sir Humphry Davy on the famous Continental tour which included many of the principal centres of learning and many of the foremost scientists of those days.

The travellers left this country on October 13th, 1813, and were absent about eighteen months, visiting France, Switzerland and the Tyrol. They landed at Deal in April, 1815, on their return, and Faraday, who had set out as little more than Davy's personal

attendant and amanuensis, came back really well equipped with knowledge and conversant, at any rate, with the work of many great men who had discussed their problems with him.

Faraday's Impressions as Recorded in his Journal.—As he wrote in a letter to Mr. R. G. Abbott from Geneva, on August 6th, 1814: " During the time I have passed from home, many sources of information have been opened to me, and many new views have arisen of men, manners and things, both moral and philosophical. The constant presence of Sir Humphry Davy is a mine inexhaustible of knowledge and improvement; and the various and free conversation of the inhabitants of those countries through which I have passed has continually afforded entertainment and instruction."

The Journal which Faraday kept during his Continental travels gives a remarkably minute description of things he saw and full details regarding Davy's scientific work. It is evident from his first entries that Faraday started with no illusions as to the possible hardships and dangers of travel in a foreign and hostile country. This was on the eve of Napoleon's disastrous defeat at Leipzig, in the year before Waterloo, and Faraday bears witness to the many perils and discomforts of travel in those days.

Week by week, as the journey progressed, one can trace in the Journal the rapid growth of Faraday's scientific knowledge, specially as he remarks in more than one place that " I write down, be they good or bad, or however imperfect, *my present impressions.*" We read of his delight at seeing a glow-worm for the first time; of his disappointment with the streets of Paris; of his meeting Ampère, Clement and Desormes; of his witnessing experiments on iodine; of his crossing the Alps; of experiments on electric gymnotus, and burning diamonds by solar heat (platinum was melted at the same time); and of his visit to Vesuvius.

Visit to Vesuvius.—This event clearly exercised a great effect upon his mind, for Faraday devotes many pages of his Journal to describing the volcano and its surroundings. Visits to the crater were made by day and by night, and Faraday obtained close views of the flames and molten lava. He must often have thought of these experiences in later years when melting steel and precious metals in his " blast furnace," and it is not impossible that his observations on the Grand Duke of Tuscany's burning glass and the crater of Vesuvius, together with his visit to the Dowlais ironworks after his return to England, had a material effect in stimulating his interest in furnaces—an interest which lasted all his life.

Visit to Dowlais Iron Works.—Faraday's visit to the famous

ironworks at Dowlais, to which reference has just been made, is of special interest in relation to his metallurgical researches. This visit took place on July 12th, 1819, that is, the same year as Faraday's paper on the analysis of wootz, and the year before the first of his two papers with Stodart on steel alloys. Clearly he was keenly interested in the various branches and applications of ferrous metallurgy during this period. As one who loved "a smith's shop and anything relating to smithery," he would naturally be fascinated by the operations at Dowlais. His own words were :

"After an early breakfast, Monday morning, July 12th, at Cardiff, I took a postchaise and proceeded on to Merthyr.

"In the afternoon I rambled with Mr. Guest's agent over the works at Dowlais.

"I was much amused by observing the effect the immensity of the works had on me.

"The operations were all simple enough, but from their extensive nature, the noise which accompanied them, the heat, the vibration, the hum of men, the hiss of engines, the clatter of shears, the fall of masses, I was so puzzled I could not comprehend them except very imperfectly.

"The mind was drawn to observe effects rather for their novelty than for their importance, and it was only when by going round two or three times I could neglect to listen to sounds at first strange, or to look at rapid motions, that I could readily trace the process through its essential parts, and compare easily and quickly one part with another."

Whatever his own practical attainments as a smith may have been, it is clear that Faraday had the advantage of a clear conception of the processes of iron-working when he embarked on his metallurgical researches.

Faraday as a Chemist

For many years Faraday regarded himself simply as a chemist, and so many and important were his discoveries in the field of chemistry that if he had made no other he would still be revered as a great chemist. Actually his chemical discoveries were subsequently overshadowed to a great extent by his even more momentous researches in other fields. Nevertheless, Faraday was a great chemist, and it must ever remain a marvel how he accomplished so much in the chemical and metallurgical fields with so little in the way of systematic early training. As we have seen, his earliest knowledge was gained by reading books which came to his master's shop when he was a bookbinder's apprentice.

Armed with no more than a patchwork of miscellaneous knowledge accumulated in this way, but recommended by his enthusiasm and by his painstaking transcription of notes taken from some of

Sir Humphry Davy's lectures, Faraday entered the Royal Institution in a comparatively humble capacity.

Effect of His Early Associations at the Royal Institution.—Once there, he had the advantage of continual association with Sir Humphry Davy and Professor W. T. Brande, and, in due course, with Dr. W. H. Wollaston, Dr. J. G. Children, Dr. S. H. Christie—all Fellows of the Royal Society—and other leading men. Even so, he had little enough in the way of systematic personal tuition. All that he learnt, and it was sufficient to win him enduring fame as a discoverer and teacher, was the result of his genius and industry applied to making the best of every opportunity, tackling every problem on its merits, and preparing information for diffusion to others in the form of papers and lectures.

There was no exaggeration in the words which appeared in the *Chemical News* on August 30th, 1867: "A truly great man is, alas! gone from among us, and a man, moreover, whose place cannot be filled. We have great chemists and great physicists left, but we have not, and probably never shall have, a Faraday." The superhuman efforts that he must have made to educate himself bore their fruit in enabling him to discover many of the secrets of nature, and pass on his store of knowledge to others. One of the greatest factors in his education was undoubtedly his Continental tour with Davy during the years 1813–1815. In the words of Professor Silvanus Thompson, "That foreign tour was for Faraday what residence at a university is for many other men; and it probably was more to him than university residence is to most men of to-day."

"*Chemical Manipulation.*"—The proof of Faraday's remarkable versatility in chemical knowledge, and his extraordinary skill and experience as an experimental investigator, is to be found in his wonderful book *Chemical Manipulation*, the first edition of which was published in 1827. This work clearly shows that Faraday was thoroughly practised in every branch of the chemistry of those days, and his detailed instructions and explanations reveal his distinguishing characteristic—that of omitting no precaution, however small. Referring to this book, Professor A. A. de la Rive, F.R.S., wrote, in his memoir of Faraday's life and works:

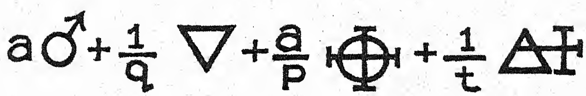
"Only those who are called upon to experiment in the domains of physics and chemistry can appreciate the immense service which this treatise has rendered to them, by teaching them a multitude of processes of detail so valuable for them to know, and of which a description was previously nowhere to be found, so that everyone was obliged to undergo an apprenticeship to them on his own account. It was necessary that a *savant* who for so many years had been struggling with the difficulties

of experimentation, and who had been able to surmount them in so ingenious a manner, should give himself the trouble to describe the means which he had employed, so that his experience might be of service to others. Faraday was this *savant*, and his object was completely attained."

In 1829, Faraday was appointed Lecturer on Chemistry at the Royal Military Academy, Woolwich; and in 1833, Fullerian Professor of Chemistry in the Royal Institution. Two years later, in 1835, he received, on the recommendation of Lord Melbourne, a well-merited pension of £300 a year from the Government.

Primitive State of Chemistry.—In considering Faraday's chemical attainments, it should be remembered that the whole science of chemistry was then in a comparatively primitive state. Much was known concerning the composition of substances and methods of preparing them, but quantitative analysis as we practise it to-day was then unknown. Means had not been discovered of determining with any considerable degree of precision all the constituents of a compound or mixture, and it was impossible to say exactly what elements were present and in what form. In this connection it is significant that Faraday nowhere gives a full analysis of his steel alloys, though he checked his products against the measured materials put into his crucibles, as explained in Chapter VI. He measured carefully what he put into his crucibles, but he did not, according to the records available, analyse chemically the alloys produced.

Chemical Notation.—Yet another instance of the comparatively primitive state of chemical knowledge at that time is to be found in the presence, on some of Faraday's specimens of steel, of the symbol ♂, representing the lance and shield of Mars, the god of war and iron. This is actually a survival from the days of alchemy, when different substances were denoted by various mysterious signs and symbols. Probably these were first adopted as a measure of secrecy and as part of the magic stock-in-trade of the alchemist. How effectively they served such purposes may be gathered from the following symbolic expression of Lavoisier:



which, interpreted into modern chemical notation, becomes simply:

$$Fe + 2H_2O + 3O_2 + 4N_2O.$$

Towards the beginning of the nineteenth century, says Professor Bernard Jaffe, M.A., of Columbia University, in his interesting book *Crucibles; the Lives and Achievements of the Great Chemists,* where he gives the above example, Berzelius introduced the writing of algebraic exponents to designate more than one atom of an element present in a compound. These exponents were later changed by two German chemists, Liebig and Poggendorff, to subscripts. These symbols and formulæ were first introduced in 1814 in a table of atomic weights published in the *Annals of Philosophy*, but, even as late as 1832, Dr. Edward Turner, of Union College, London, in the fourth edition of his *Elements of Chemistry*, used these symbols with the apology that he "ventured to introduce chemical symbols as an organ of instruction."

Every fresh example of the enormous disparity between the scientific knowledge and methods of to-day and those of even a hundred years ago comes as something of a shock. The advance that has been made should encourage those of to-day to further efforts, and, at the same time, it should increase our respect for those who first worked on the road to knowledge. Theirs was a difficult task indeed, and made more so by a host of mistaken ideas and defective methods.

Faraday's Metallurgical Work

His First Real Research.—Faraday's researches on steel and steel alloys were really the first of his investigations which can be described as researches. His earlier papers were small and of comparatively unimportant nature. One, published in 1816, dealt with "The Analysis of the Native Caustic Lime of Tuscany"*; another, in 1819, with "The Separation of Manganese from Iron."† The subject of the latter is of rather special interest, for although Faraday's first investigation on iron had direct reference to the metal manganese, it is a curious fact that manganese is not to be found except as traces in any of the specimens of steel alloys which he left behind him.

Researches in Ferrous Metallurgy.—His researches and investigations on ferrous metallurgy may be said to have commenced in 1819 with "The Analysis of Wootz or Indian Steel." ‡ In this paper specific mention was made that he was engaged with Stodart on the research regarding steel alloys. Then came the two important papers jointly with Stodart, viz. "Experiments on the

* *Q.J.S.*, Vol. I., pp. 260—261.
† *Q.J.S.*, Vol. VI., pp. 357—358.
‡ *Q.J.S.*, Vol. VII., pp. 288—290.

Alloys of Steel made with a view to its Improvement" (Royal Institution, 1820),* and "On the Alloys of Steel" (Royal Society, 1822).†

From the year 1822, when Faraday was thirty-one years old, to the time of his death in 1867, at the age of seventy-six years, there were no other papers by him bearing to any appreciable extent on alloys of steel or ferrous metallurgy. It is true that there were papers on "Magnetic Relations and Characters of the Metals" in 1836 and 1845, but these concerned magnetic rather than metallurgical investigations; and, in 1861, there was the paper "On Platinum," but this had no relation to the question of alloying platinum with steel.

Non-ferrous Metals.—Faraday was much interested generally in metals, and paid most attention to iron, steel and steel alloys.‡ Besides his paper on platinum, just mentioned, one of his most interesting investigations on non-ferrous metals was his examination of the relations of finely divided gold to light.§ This was a physical rather than a metallurgical investigation, but it brought forth some exceptionally interesting information concerning that extraordinary ductile metal gold, an ounce of which can be hammered into 750 leaves each about 3 inches square. By pouring a solution of potassium cyanide on to a leaf of gold spread on a glass plate, Faraday obtained extremely thin films of gold and was thus enabled to make interesting observations concerning the behaviour of gold to light. Ordinary gold leaf appears green by transmitted light, but this changes to ruby red when the attenuated film is heated to 316° C. The colour of ruby glass is due to the presence of metallic gold in a very fine state of division.

The Period of the Steel Alloy Researches

This period occurred between 1819 and 1824. Faraday certainly continued his researches on steel alloys until the summer of 1824, that is, for some time after Stodart died, as witness the notes in his diary referred to on p. 125, but there are only a few words of record to be found subsequent to the Royal Society paper of 1822. Practically speaking, Faraday's researches on steel and its alloys were concentrated into the period 1819–1822, and to the recorded evidence of the large amount of work which he accomplished during these years we may add an unknown amount for

* *Q.J.S.*, Vol. IX., pp. 319—330.

† *Phil. Trans.*, March 21st, 1822, pp. 253—270.

‡ Faraday gave a course of valuable lectures before the City Philosophical Society in 1817 and 1818 dealing with metals.

§ *Phil. Trans.*, 1857, p. 145.

the work done in 1823. Work was still proceeding in 1824, but there is no evidence that it was on any considerable scale, either as regards number of experiments or the weight of alloys prepared.

Other Problems then being Solved.—It must not be thought, however, that Faraday was ever able to devote the whole of his time and energy to the researches on steel alloys for any considerable period. On the contrary, he was engaged more or less simultaneously with so many diverse problems that the marvel is how he was able to find the solution to any of them. A letter which he wrote, in December, 1820, to Miss Sarah Barnard, whom he married later, reveals the strain to which he was subjected:

"Royal Institution: Tuesday evening.

"MY DEAR SARAH,

"It is astonishing how much the state of the body influences the powers of the mind. I have been thinking all the morning of the very delightful and interesting letter I would send you this evening, and now I am so tired, and yet have so much to do, that my thoughts are quite giddy, and run round your image without any power of themselves to stop and admire it. I want to say a thousand kind, and, believe me, heartfelt things to you, but am not master of words fit for the purpose; and still as I ponder and think on you, chlorides, trials, oil, Davy, steel, miscellanea, mercury, and fifty other professional fancies swim before and drive me further and further into the quandary of stupidness.

"From your affectionate
"MICHAEL."

At the date of their marriage, on June 12th, 1821, Faraday was thirty and Miss Barnard twenty-one years of age.

In the year 1821, that is midway between his two papers on steel alloys, when he must have been very busily engaged with the later experiments on steel and alloys, and with the arrangements for trials on a larger scale at Sheffield, Faraday made his discovery of the rotation of a wire carrying an electric current round a magnetic pole. This discovery was undoubtedly responsible for Faraday's devoting himself more fully to electrical investigations during the following years and, from this point of view, it may be regarded as one of the factors contributing to his abandoning the work on steel alloys.

As though the researches on steel and the above-mentioned electrical investigations were not enough to occupy his time and brain, Faraday published, in 1821, his important paper on the condensation of gases, in which he announced for the first time the fact that gases are simply the vapours of volatile liquids.

In 1824, Faraday was elected a Fellow of the Royal Society, and

it is interesting to note that his eminence in chemical science was made the basis of his nomination paper; this will be found on p. 22.

Metallurgical Researches Finished in 1824.—From the summer of 1824 onwards, Faraday does not appear to have pursued his investigations of steel alloys, and in 1863, owing to his lapse of memory, he could not even tell his friend Dr. Percy what had happened to the now famous steel specimens described in this book, or where they could be found. Thus ended the years of labour based on such high hopes—in complete forgetfulness of where the fruits had been stored! The fruits themselves are now found to be of great interest and value, and they contain to-day, as they did more than a century ago, the seed from which the whole family of modern alloy steels might have sprung.

Faraday the Pioneer of Steel and Alloys.—Circumstances led Faraday into other and, as it happened, more immediately fruitful lines of research after the year 1824, and there was none to carry on his steel researches on his lines. At the time, no one appears to have appreciated their possibility and their importance; and it must be remembered that there were no immediate needs for superior materials such as alloy steels. Also, there were no facilities for their discovery, investigation and manufacture at all comparable with those existing fifty or sixty years later. These probably are the reasons why Faraday's work remained isolated, almost forgotten, and certainly under-estimated for so many decades.

Faraday was undoubtedly the first to embark on a considered, well-planned and extensive series of researches on alloy steels; and even though his particular alloys found no lasting practical use, his research, even with our present wide knowledge of alloy steels, contains much valuable information.

Whatever our feelings as to the extent to which we should recognise Faraday as the harbinger of modern alloy steels—and, personally, the author maintains that full credit should be given to him for this—we can all agree that his researches were far from being a failure and that true research work on alloy steels began with Michael Faraday.

Faraday and the Royal Institution

From the time of his first engagement at the Royal Institution in 1813, Faraday's life and works may be said to have been inseparably bound up with that institution. Both Faraday and the Royal Institution benefited by this long association, extending

for some fifty-four years—Faraday as it gave him the opportunity he desired of carrying on his scientific work, this, too, without regard to any material gain, and the Royal Institution as it secured the life-long services of one of the greatest geniuses of the age.

Within a few months of his entering the service of the Royal Institution, Faraday left it for eighteen months in order to accompany Sir Humphry Davy on his Continental tour. When Faraday intimated his desire to go with Davy, the managers of the Royal Institution permitted him to resign his situation and ordered that he should be paid a month's wages on his departure ; *the assistant porter was engaged as laboratory assistant at the same wage as had been paid to Faraday.* Such was Faraday's status in the year 1813 ; an assistant porter could take over his position !

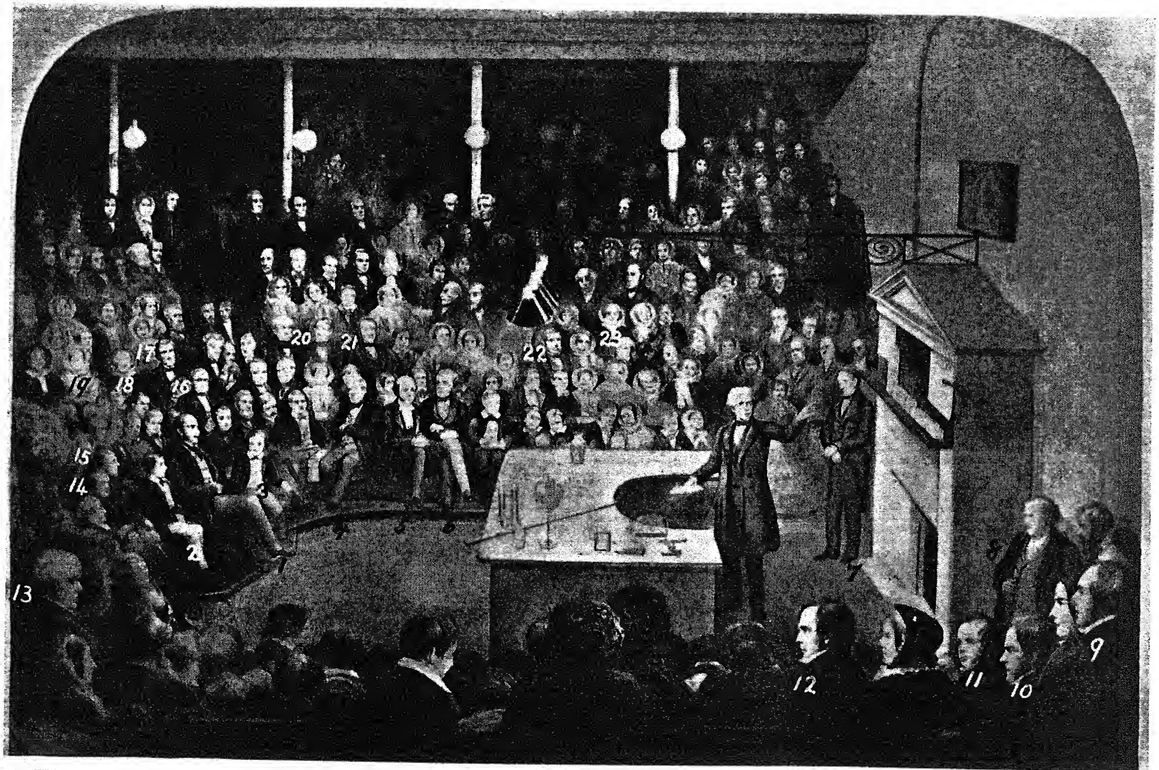
A change was soon to come. Faraday, who left England as the general assistant and amanuensis of Davy, soon attracted the attention of distinguished scientists abroad, and it seems that Davy was considerably annoyed on some occasions by the evident respect with which his junior was treated. This, however, was a passing phase on which we need not dwell. The important fact is that Faraday had exceptional opportunities of making himself acquainted with the work and methods of many of the leading men of science in those days. Those opportunities he utilised to the full, and by his ability and simple charm of manner he laid foundations of an international reputation which grew rapidly and continually until the end of his life.

On his return to England in 1815, he was taken back into the service of the Royal Institution. The former assistant porter was made porter again, and Faraday was engaged for the laboratory, the mineralogical section of the Institution, and as superintendent of the apparatus at a salary of thirty shillings a week. Outwardly, he came back much as he went, but his whole outlook had been immeasurably broadened by his Continental experiences, and his work from now onwards was on a higher plane. He was made Director of the Laboratory in 1825, and first Fullerian Professor of Chemistry in 1833.

It has been rightly said that from 1815 the life of Faraday and the history of the Royal Institution became inseparable, and from 1825, when Faraday was made Director of the Royal Institution Laboratory, the Institution was for many years kept alive by his unselfish devotion to its welfare. When making his great electrical and magnetic researches, Faraday's salary at the Royal Institution was only £100 per annum, and although he had some outside

PLATE IV

PRINCIPAL PORTRAITS OF THOSE ATTENDING THE LECTURE BY MICHAEL FARADAY AT THE ROYAL INSTITUTION, DECEMBER 27TH, 1855, COMMEMORATING THE ATTENDANCE OF H.R.H. THE PRINCE CONSORT, ACCOMPANIED BY H.R.H. THE PRINCE OF WALES AND H.R.H. PRINCE ALFRED, AT THE JUVENILE COURSE OF LECTURES, 1855–6, ON "THE DISTINCTIVE PROPERTIES OF THE COMMON METALS."



1. H.R.H. the Prince Consort.
2. H.R.H. the Prince of Wales.
3. H.R.H. Prince Alfred.
4. General Sir Geo. Pollock.
5. Rev. J. Barlow, Secy.
6. Dr. Bence Jones.
7. Mr. Anderson, the valued assistant.
8. Sir James South, Astronomer.
9. George Barnard, Esq.
10. Mr. Frederick Pollock.
11. Dr. Lancaster.
12. Dr. Roxburgh.
13. Mr. James Walker, C.E
14. Dr. Becker.
15. Sir Chas. Fellowes.
16. Dr. Granville.
17. Professor Tyndall.
18. Mrs. Barlow.
19. Miss Moore (niece of Sir John Moore).
20. Sir Chas. Lyell.
21. Lyon Playfair.
22. Mr. Warren de la Rue.
23. Mrs. Faraday.
24. Sir Roebuck Murchison.

Reproduced through the kindness of Mr. A. Evelyn Barnard.

Artist, ALEX. BLAIKLEY (1816–1903).

[To face p. 20.

work, and took a few pupils, his total income must have been quite small.

Early Lectures.—The lectures which Faraday delivered for so many years at the Royal Institution constituted an important part of his life's work and made him one of the most beloved and respected of men to all who had the privilege of hearing him ; also, they did much to strengthen the position and extend the influence of the Royal Institution itself. Faraday's first experience in lecturing appears to have been gained by giving science lectures* at the rooms of the City Philosophical Society, Dorset Street, Fleet Street, and one of his first acts after his appointment as Director of the Laboratory at the Royal Institution in 1825 was to inaugurate evening meetings of the members for the discussion of scientific problems. These meetings, held first in the laboratory, and later in the theatre, with ladies admitted to the gallery, were the forerunners of the famous Friday evening discourses. To Faraday, also, we owe the commencement of Christmas lectures, which are still such a source of delight and instruction to the boys and girls of to-day.

The first of the Friday evening discourses was delivered on February 3rd, 1826, the subject being caoutchouc. Faraday's courses of lectures at the Institution began in April, 1827, with one on chemical philosophy, and ended in 1860 with his Christmas course on the chemical history of a candle. His last Friday evening discourse, delivered on June 20th, 1862, was a remarkably brilliant one on gas furnaces. The notes which he made for this, his last lecture, says Bence Jones, are very touching and very characteristic.

They were as follows :

"Personal explanation—years of happiness here, but time of retirement ; loss of memory and physical endurance of the brain.

"1. Causes—hesitation and uncertainty of the convictions which the speaker has to urge.

"2. Inability to draw upon the mind for the treasures of knowledge it has previously received.

"3. Dimness, and forgetfulness of one's former self-standard in respect of right, dignity, and self respect.

"4. Strong duty of doing justice to others, yet inability to do so.

"Retire."

Faraday died on August 25th, 1867, and at their meeting on November 4th, 1867, the managers of the Royal Institution passed a resolution to the following effect :

"Resolved that the Members of the Royal Institution sympathise most deeply with Mrs. Faraday in the loss of their Professor and Friend.

* Nos. 13 to 16 were all on metals.

"His energy and genius were rewarded by discoveries that have made their Institution renowned throughout the world; whilst his judgment and kindness were so frequently and so well shown in all that related to the good of Members that they feel his departure from among them as a misfortune which no words can adequately express."

In this resolution there is no word of exaggeration, and it would hardly have been possible to express more fittingly the services rendered by Faraday to the Members, the Institution and the world at large.

Faraday and the Royal Society

Faraday was elected a Fellow of the Royal Society on January 1st, 1824. Although Sir Humphry Davy did not sign the nomination form, this had no effect on the issue, and within a month Davy was writing to Faraday in very friendly terms. The terms of the certificate signed by thirty persons, including Wm. H. Wollaston, J. G. Children, Wm. Babington, Sir W. Herschel, J. South and Davies Gilbert, were as follows:—

"Mr. Michael Faraday, a gentleman eminently conversant in chemical science, and author of several papers, which have been published in the *Transactions of the Royal Society*, being desirous of becoming a Fellow thereof, we, whose names are undersigned, do of our personal knowledge recommend him as highly deserving that honour, and likely to become a useful and valuable member."

This certificate had to be read at ten successive meetings before the ballot. When the ballot was taken there was only a single black ball. One cannot but wonder who was sufficiently misguided as to attempt to deny admission to the man who subsequently received unsought no fewer than ninety-three honorary titles and tokens of merit from leading bodies all over the world. As Faraday said, in later years: "One title, namely that of F.R.S., was sought and paid for; all the rest were spontaneous offerings of kindness and goodwill." It is a pity that the one honour deliberately sought by our great scientist should have been opposed even by a single individual.

In 1857, some thirty-three years after Faraday was elected a Fellow of the Royal Society, he declined the presidency of that great body, notwithstanding the most earnest pleading of certain members of the Council. The retiring president himself (Lord Wrottesley), Mr. Grove and Mr. Gassiot went as a deputation to Faraday to urge his acceptance of the proffered honour, but in vain. Dr. John Percy, who was also one of the Council, then wrote privately to Faraday, begging him to reconsider his decision

"in the best interests of science, and to establish an important principle in reference to the society for which many have, as you know, so long and arduously struggled." To this Faraday replied :

"ROYAL INSTITUTION,
"May 21st, 1857.

"MY DEAR PERCY,

"Your letter is very kind and earnest, and I thank you heartily for it, but I may not change my conclusion. None can know but myself how unfit it would be.

"Ever affectionately yours,
"M. FARADAY."

Here, again, one may wonder ; why should Faraday persist in his refusal, and why would his acceptance have been "unfit" ? One thing at least is clear ; then, as ever, Faraday shunned rather than sought any appointment, however distinguished, which might distract his thoughts or divert his energies from the active prosecution of his researches. Unsparing in his efforts where the pursuit of knowledge was concerned, he would give neither time nor attention to self-glorification or personal profit.

FARADAY—THE MAN

One of the greatest, if not the greatest, experimental philosophers the world has ever known, Michael Faraday was also one of the best of men, and was regarded with the utmost affection by all who knew him. Rising from the humblest origin to a position and reputation which brought him the highest honours and caused him to be consulted by eminent men and even Governments, he remained to the last loyal to all his friends and free from any trace of pride. None, however humble, sought his counsel or his assistance in vain.

As Bence Jones, his biographer, says : "He loved truth beyond all other things ; and no one ever did or will search for it with more energy than he did. Kindness was the rule of his life ; kindness to everyone, always—in thought, in word, in deed. His energy was no strong effort for a short time, but a lifelong lasting strife to seek and say that which he thought was true, and to do that which he thought was kind. One at least of his natural qualities was greatly strengthened by his strong religious feeling, which produced what may well be called his marvellous humility. His standard of duty was supernatural, and throughout his life his faith led him to act up to the very letter of it."

On being asked by a young inquirer the secret of his uniform success, Faraday replied : "The secret is comprised in three words—Work, Finish, Publish." Certainly his life affords a

striking example of the application of this golden rule. He worked so diligently that the Royal Society catalogue gives a list of 158 papers under his name, apart from four written in collaboration with others. Almost every one of these represented the results of many experiments, for he was first and foremost an experimentalist. "Without experiment," he said, "I am nothing. I was never able to make a fact my own without seeing it; I could trust a fact, and always cross-examined an assertion." All his principal researches offer examples of his pertinacity in experiment, and his famous lectures and discourses were illustrated by innumerable experimental demonstrations.

His genius, ability and industry were first proved by the events of his early youth. Within ten years from 1803 the newspaper boy had qualified as a journeyman bookbinder and acquired such a store of knowledge by private study and experiment that the great Sir Humphry Davy engaged him as laboratory assistant and, a few months later, took him abroad as his personal assistant. During the course of that tour Faraday attracted the attention of some of the most eminent scientists in Europe—within a few months of his leaving his trade of bookbinding!—and ten years later he was elected a Fellow of the Royal Society and had already received several of the high distinctions conferred upon him by learned institutions at home and abroad.

Faraday's voluminous notes of Davy's lectures won him his first engagement at the Royal Institution, and the same spirit of industry and patience is evidenced by the index of the first twenty volumes of the *Quarterly Journal of Science and the Arts,* the official journal of the Royal Institution, in which there appears the words "made by M. Faraday." At this time Faraday was thirty-five years of age and intensely busy in the responsible post of Director of the Royal Institution laboratory. He found time to perform this tedious task of indexing because it helped on his work in other directions. Otherwise he would not have done it. The Athenæum Club was founded in 1823, and Faraday was its first secretary, but, "finding the occupation incompatible with his pursuits, he resigned in May, 1824." No trouble was too great and no task too menial where the advancement of knowledge was concerned, but nothing would tempt him to expend his energies in other directions. Truth and kindness were the aim of all his work, and of his ceaseless striving towards them it may truly be said *Labor omnia vincit improbus.* He was famous as a teacher no less than as a discoverer. He devoted his life to science, with but one single aim—to advance its position in the world, and the benefit

of mankind, without fear or favour to rich and poor alike. No monetary or selfish considerations ever entered his mind.

Faraday's Influence on Scientific Advance

Apart from the direct contributions to knowledge which Faraday made by his own discoveries, he exerted a wide and far-reaching influence on the development of truly scientific methods by insisting on the importance of experimental research and verification. In his hands, experiments became instruments of extraordinary power. He was no lover of mathematics and, in a letter to Clerk Maxwell in 1857, he expressed a sentiment which many will endorse. "There is one thing I would be glad to ask you," he wrote. "When a mathematician engaged in investigating physical actions and results has arrived at his own conclusions, may they not be expressed in common language as fully, clearly and definitely as in mathematical formulæ? If so, would it not be a great boon to such as we to express them so—translating them out of their hieroglyphics that we also might work upon them by experiment?"

Helmholtz, in his Faraday Lecture of 1881, said: "It is in the highest degree astonishing to see what a large number of general theorems, the methodical deduction of which requires the highest powers of mathematical analysis, he found by a kind of intuition, with the security of instinct, without the help of a single mathematical formula. . . . With a quite wonderful sagacity and intellectual precision, Faraday performed in his brain the work of a great mathematician without using a single mathematical formula. . . . The fundamental conceptions by which Faraday was led to these much-admired discoveries have not received an equal amount of consideration. They were very divergent from the trodden path of scientific theory, and appeared rather startling to his contemporaries. His principal aim was to express in his new conceptions only facts, with the least possible use of hypothetical substances and forces. This was really an advance in general scientific method, destined to purify science from the last remnants of metaphysics. Faraday was not the first, and not the only man, who had worked in this direction, but perhaps nobody else at his time did it so radically."

Significantly enough, there appears in the first edition of Faraday's *Chemical Manipulation* (1827) the following excellent motto:

> "Ce n'est pas assez de savoir les
> principes, il faut savoir MANIPULER.
> *Dictionnaire de Trevoux.*"

This may truly be said to be the basis of all Faraday's work.

Benefits Derived from his Discoveries.—Taking him all in all, Faraday was one of the most brilliant and versatile scientific immortals the world has ever known. Of him, the term "immortal" may be used with special aptitude, for the future progress of researches which he inaugurated will perpetuate and enhance the glory of this great investigator. Vast industries have been built on foundations which he laid, and these also will grow continually and carry his name from generation to generation. The electrical industry is perhaps the greatest of all the material results of the labours of one who cared nothing for material profit, but there are others which are also of vast importance. Faraday's discovery of benzol led to one of the greatest industrial successes ever achieved by chemistry, and his determination of the composition of naphthalin led Laurent to some of the most important theoretical discoveries of the age. From Faraday's many discoveries and inventions which he never patented, and of which he never made commercial use, the world is benefiting and will continue to benefit on an immense scale.

Professor Max Planck has recently well said: "Man has progressed because he has acquired a greater mastery of natural laws; this mastery has necessitated a progress in intelligence, and it has led to great material progress." No one has ever done more than Faraday to bring about progress in our mastery of natural laws; in himself he was a glorious example of man's progress in intelligence and methods of thought; and from his labours there has sprung material progress vast beyond estimation.

One stands amazed at the number, diversity and importance of his discoveries. While still engaged on his investigations of steel alloys he discovered the chlorides of carbon, discovered electromagnetic rotations, and made various successful experiments on the liquefaction of gases. Then came his discovery of benzene, and his important researches on the manufacture of optical glass. In 1827 he began his courses of lectures at the Royal Institution, and published his book *Chemical Manipulation.*

His most famous discovery—that of magneto-electric induction, the foundation of modern electrical engineering—was made in 1831. Thereafter he continued his electrical, magnetic and associated researches until the end of his active career, without, however, neglecting investigations in other branches of inquiry. He discovered the laws of electrochemical decomposition, and demonstrated that magnetism acts both on matter and on energy. He made important investigations concerning dielectrics and specific inductive capacity, and others relating to many optical phenomena.

He introduced the ideas of polymerism and isomerism, and to him we owe the revolution of thought which substituted the wave theory of energy for the supposed emission of imponderable matter which had hitherto been associated with light, heat and electricity. These, be it noted, are only a few of the more important discoveries made by Michael Faraday. For a full statement of them, one would have to refer to every one of his published papers—for each contained something original—and to the mass of unpublished information in his journal, for even his negative results and his failures often amount to discoveries.

Eulogies from Abroad

It is easy to be carried away by enthusiasm for one's fellow-countrymen, but, where Faraday was concerned, the sentiments expressed by competent authorities in other countries were at least as complimentary as anything ever said or written concerning him in England.

Diplomas, Medals and Honours.—The fact that he received nearly a hundred diplomas, medals, honorary memberships and other marks of merit from many different countries proves the high estimation in which he was held. Briefly, these distinctions were as follows :

Diplomas, Memberships, etc.

Great Britain	33
Italy	12
France	10
Germany	13
United States of America	5
Others (Belgium, Denmark, Holland, Russia, Spain, Sweden, Switzerland)	14
	87

Medals.

Copley (two), Royal (two), Rumford, Grande Medaille d'Honneur (Paris)	6

In the *Proceedings of the Académie des Sciences* there is clear evidence of the high esteem in which Faraday was held, even at the early dates of 1821–1823 (corresponding to the later stages of his researches on alloy steels). Thus at the meeting of the Académie on November 19th, 1821, Ampère communicated particulars of Faraday's experiment on the rotation of a magnet

or a current-carrying conductor by mutual action between the two. (It will be noted that Faraday had already begun to establish his reputation as an electrical investigator.) Again, at the meeting on October 27th, 1823, the thanks of Faraday were communicated for his appointment as *Correspondant* in the *Section de Chimie*—an honour which testified to his chemical attainments.

Eulogies by de la Rive and Dumas.—The various biographies of Faraday published in this country are very widely known, specially the classic works among them. Innumerable obituary notices were published concerning him, and some of the more striking passages from these are to be found in certain of the biographies. Instead, therefore, of repeating what is already fairly general knowledge, let us turn to two eulogies by famous foreigners, one by Professor A. A. de la Rive, of Geneva (the son of the professor to whom Faraday wrote an account of his steel alloy experiments), the other by Monsieur J. B. Dumas, Secretary of the French Académie des Sciences. Each of these is a remarkable testimony to the reverence and affection in which Faraday was held, not only by his own countrymen, but by all who came into contact with him or knew his works.

Professor A. A. de la Rive's eulogium of twenty-seven pages, translated from the *Bibliothèque Universelle*, October 25th, 1867, *Arch. des Sci.*, pp. 131–176, and published in the *Philosophical Magazine*, December, 1867, presents an admirable review of Faraday's life and his work in the fields of chemistry and kindred subjects, electricity and magnetism, electrochemistry, electrical induction, and the action of magnetism and electricity upon light. Professor de la Rive regarded electrical induction as the most important of Faraday's discoveries, and the action of magnetism and electricity on light as the most brilliant. It is, however, with his appreciation of Faraday as a scientist and a man that we are specially interested ; on this, his words may be quoted in full :

" Without children, a complete stranger to politics or to any kind of administration, except that of the Royal Institution, which he directed as he would have directed his own house, having no interest but that of science, and no ambition but that of advancing it, Faraday was of all savants the one most completely and exclusively devoted to the investigation of scientific truth of which the present century offers us an example.

" One may easily understand what must be produced under such circumstances by a life thus wholly consecrated to science, when to a strong and vigorous intellect is joined a most brilliant imagination. Every morning Faraday went into his laboratory as the man of business goes to his office, and then tried by experiment the truth of the ideas

which he had conceived overnight, as ready to give them up if experiment said "*no*," as to follow out the consequences with rigorous logic if experiment answered "*yes*." His everyday labour experienced no interruption, except the few hours which he devoted from time to time to the exposition in the theatre of the Royal Institution, before an audience equally numerous and select, of certain parts of physics and chemistry. Nothing can give a notion of the charm which he imparted to these improvised lectures, in which he knew how to combine animated and often eloquent language with a judgment and art in his experiments which added to the clearness and elegance of his exposition. He exerted an actual fascination upon his auditors; and when, after having initiated them into the mysteries of science, he terminated his lecture, as he was in the habit of doing, by rising into regions far above matter, space and time, the emotion which he experienced did not fail to communicate itself to those who listened to him, and their enthusiasm no longer had any bounds."

In concluding his estimate of the special characteristics of Faraday's labours and the influence which they exercised on the progress of science, de la Rive used the following remarkable words:

"The first character that strikes us is their number. What Faraday published in the form of memoirs from 1820 to 1855 is incredible. And what would it have been if, side by side with the multitude of experiments which he has made known, we placed in a parallel series those which he never published? It is true that if he has left them buried in his journal, it is because they gave him negative results; but from how many fruitless essays and erroneous attempts he would have preserved scientific men if he had not been so discreet!

"A second character is the exactitude of the results obtained: I do not think that Faraday has once been caught in a mistake; so precise and conscientious was his mode of experimenting and observing. It must be admitted that in him the hand marvellously seconded the head; he was of remarkable dexterity, and possessed a practical talent, rare and precious in men of science, which enabled him, when necessary, to construct and modify his apparatus for himself, with the view of attaining with more certainty the desired result.

"A third character of quite a different kind, and of much greater value, is the originality of the works of Faraday. A disciple of Davy, he undoubtedly shows traces of the school from which he came, especially in the choice of the subjects of which he treats; but he does not blindly follow either the method or the steps of his master, and, soon quitting the beaten track, he strikes out a path for himself."

In the great work of demolishing erroneous ideas which proceeded during the earlier part of the nineteenth century, and in the construction of the bases on which all subsequent advance was founded, Faraday was "one of the first, most active and most persevering. Therefore his works," says de la Rive, "will always

be regarded as corner stones in the new edifice which we are now endeavouring to construct." Those words, written in 1867, hold good to-day. We are still labouring on the edifice of new knowledge, which will always be heightened and can never be completed. Faraday's works are still regarded as corner stones in that edifice, and so they will remain for all time, for Faraday sought and discovered truth, which is eternal.

No less glowing, sincere and convincing than de la Rive's eulogy is the commemoration speech of M. Dumas, which constitutes an admirable biography of Faraday and affords a remarkable testimony to the brilliance and importance of his work, and the almost supernatural beauty of his character.

CHAPTER III

THE STAGE AND THE *DRAMATIS PERSONÆ*

Introductory

In building up the whole story of Faraday's association with steel and alloys of steel, and in attempting to gain an appreciation of the conditions under which he worked and the assistance he received, it is helpful to learn something of the persons with whom he came in contact, specially as regards his researches on steel. It is of interest, too, to recall the circumstances of the foundation of the Royal Institution, the stage on which Faraday performed almost the whole of his life-work, and where many of the others with whom we are concerned took their part. More than passing reference may fairly be made to those who introduced Indian steel or wootz into this country, for the excellent qualities of this material and the desire to imitate them were largely responsible for Faraday's interest in steel and steel alloys. Concerning the general state of knowledge in ferrous metallurgy during the opening years of the nineteenth century more is said in Chapter IV. Before considering that aspect of the subject, let us describe the stage and assemble our *Dramatis Personæ*.

The Royal Institution

The Royal Institution is officially described as " an association of men and women for the advancement of natural knowledge. In general, its objects are to prosecute scientific and literary research ; to illustrate and diffuse the principles of inductive and experimental science ; to give opportunities for social intercourse among those who are attached to science ; and to afford them the means of collective and individual study."

Founded in 1800.—Founded in 1800 by Sir Benjamin Thompson, Count von Rumford, with the support of Mr. Bernard (afterwards Sir Thomas Bernard, the first Treasurer), Sir Joseph Banks, then President of the Royal Society, and other original subscribers, the Royal Institution was granted a Royal Charter on January 13th, 1800, by George III., and during the period of more than 130 years which has since elapsed the Royal Institution has played a wonderful and unique part in the history of our nation. It has indeed

helped to encourage, nurture and develop some of the greatest scientists the world has known.

In a letter from Faraday dated March 20th, 1848, written from the Royal Institution, to Weld, the author of the interesting *History of the Royal Society*, 1848, in two volumes, he made the following statement:

"According to the earliest document I can find, the first meeting held for the purpose of founding the Institution, was on the 9th March, 1799, at the house of Sir Joseph Banks, in Soho Square. It is called a Meeting of the Managers, and there were present Sir Joseph Banks, the Earl of Morton, the Earl Spencer, Count Rumford, Richard Clark, Esq., and Thomas Bernard, Esq. These were the men; and at that meeting they made Sir Joseph Banks chairman, and Mr. Bernard secretary. The title and purposes of the Institution, as given at that time, are as follows:

"INSTITUTION.—For diffusing the knowledge, and facilitating the general introduction, of useful mechanical inventions and improvements: and for teaching, by courses of philosophical lectures and experiments, the application of science to the common purposes of life.

"You will see that no idea of the research that grew up in the time of Young and Davy entered into the conceptions of the founders. The first meeting of the proprietors (now replaced by those we call members) took place on the 20th of April of the same year.

"Ever truly yours,

"M. FARADAY."

Although the Institution owed its origin entirely to Rumford it is probably not too much to say that it would have failed but for the work of Davy and Faraday. In the words of Henry Bence Jones, from his book *The Royal Institution:* "The history of thirteen years of the life of Davy, like that of fifty of the life of Faraday, is closely interwoven with the history of the Royal Institution. Their lives were the life of the place. From 1815 the life of Faraday and the history of the Royal Institution become inseparable, and from 1824 it was kept alive by his unselfish devotion to its welfare." This mention of the date 1824 is perhaps of special significance. It was in this year that Faraday performed his last experiments with steel alloys, and it is at least conceivable that Faraday's feelings of responsibility towards the Institution and anxiety for its welfare led directly or indirectly towards his discontinuing the researches on steel alloys which had occupied so much time and doubtless involved considerable expense without holding out any prospect, as they seemed to him, of bringing out important discoveries.

Facilities for Research.—This famous Institution, the scene of nearly all Faraday's labours, afforded him precisely the conditions

of work which most appealed to him. The monetary reward was small, for the Institution was poor in those days, but that was a matter of indifference to Faraday, who was always content to accept as little as would cover his modest requirements provided that it was not "the indicator of the character of the appointment." On the other hand, the ample laboratory accommodation and the excellent facilities available (as judged by the standards of that time), together with the absence of restrictions, and the opportunity of imparting information to others in the course of lectures, were peculiarly appropriate to Faraday's abilities and temperament. In large measure, the Royal Institution helped to make Faraday what he was, and it is equally true that he, in return, greatly enhanced the reputation and influence of the Royal Institution.

Housed in a substantial building in Albemarle Street, the Royal Institution is known in every part of the world as one of the foremost centres of scientific thought and discovery. It has played, and will continue to play, a great part in scientific discovery and investigation, and in the diffusion of scientific knowledge. To present a paper or deliver a lecture before the Royal Institution is an honour highly prized by even the most eminent men of science.

Over a period of 130 years the laboratories of the Institution have been associated with the researches of Young, Davy, Brande, Faraday, Tyndall, Frankland, Odling, Gladstone, Dewar, Strutt (third Lord Rayleigh), Thomson, Rutherford and Bragg. No other institution in the world can claim such a record of research and discovery as that of the Royal Institution. Experiments carried out in its laboratories have led to the establishment of great industries of ever-increasing importance, and innumerable additions have been made to the world's knowledge of scientific facts and principles. The cost of all this work has been borne by the contributions of members, supplemented by the gifts of benefactors, and most powerfully aided by the self-denial of the eminent men who have lived and worked in the Institution.

The present General Secretary of the Institution, Mr. Thomas Martin, M.Sc., has undertaken the important work of preparing Faraday's famous diary for publication, and the author is specially indebted to him and Mr. W. J. Green, B.Sc., for assistance rendered in searching for specimens of Faraday's steel and alloys amongst the large accumulation of experimental apparatus and other materials.

Sir Benjamin Thompson (Count von Rumford), F.R.S. (1753–1814)

In the remarkable career of this great man there is, perhaps, nothing which gives him a better title to the enduring remembrance and gratitude of humanity than his work of founding the Royal Institution.

Born at North Woburn, Mass. (U.S.A.), Thompson was apprenticed to a storekeeper at the age of fourteen years. A few years later he attended lectures at Harvard University and acquired a knowledge of medicine and surgery. He held various appointments under the Colonial Office, was knighted by George III. in 1784, and subsequently spent eleven years in Munich, where he rendered valuable public services and whence he returned, in 1795, with the title of Count von Rumford.

His scientific activities were many and various. He experimented with gunpowder and projectiles, conducted important investigations in heat and economical combustion, and in electricity and light. He was elected a Fellow of the Royal Society in 1779, and, himself the recipient of many honours, he established by his munificence honours for others in the form of medals to be awarded by the Royal Society and the American Academy of Arts and Sciences; also a professorship of physics at Harvard.

Truly a "citizen of the world," Rumford appears to have been as familiar with French, German, Italian and Spanish as with English, and his activities and reputation were remarkable in America, England and Bavaria alike. Yet of all his work the most important and the most enduring was the foundation of the Royal Institution for the diffusion of the knowledge of new improvements and for teaching an application of science to the useful purposes of life. Rumford himself was the first Secretary of the Institution, he designed the lecture-room, and he superintended the *Journal* for about two years until he went to Bavaria in 1802. To Rumford is due the credit for establishing the Royal Institution which later gave Faraday his opportunity; but Davy first and Faraday later, and in much greater measure, deserve the credit of raising the Royal Institution to world-wide fame, fulfilling a purpose which is realised nowhere else in quite the same manner and degree.

Benjamin Huntsman (1704–1776)

Though Huntsman died some years before Faraday was born, no description of the state of ferrous metallurgy early in the nineteenth century would be complete without reference to the impor-

COUNT RUMFORD, F.R.S.
1753–1814.

[*To face p.* 34.

Josiah Wedgwood, F.R.S.
1730–1795.

To face p. 35.]

tant work accomplished by Huntsman, specially in regard to the production of crucible cast steel, a matter which is further discussed in Chapter IV.

Starting business as a clockmaker and locksmith at Doncaster, Huntsman soon began to experiment in steel manufacture in order to obtain a better grade of material for his own use. About the year 1740 he moved to Handsworth, near Sheffield, and there he perfected his crucible cast steel. Curiously enough the merits of this material were recognised in France earlier than they were in this country, and it is said that the competition of French cutlery made from steel exported by Huntsman was finally the means of compelling Sheffield cutlers to take up its use.

Josiah Wedgwood, F.R.S. (1730–1795)

Many members of the family of Wedgwood were potters in Staffordshire during the seventeenth century, and Josiah Wedgwood was put to that trade before he was ten years old. A skilled craftsman himself, he was also a man of originality, energy, and business acumen. By the time he was thirty years of age he had a pottery of his own, and was soon engaged in the production of wares of remarkable beauty and quality. His achievements undoubtedly influenced the whole subsequent development of pottery manufacture, and he was also a man of culture whose interests extended far beyond his own trade. For example, he engaged actively in the movements for improved roads and canals and for the establishment of schools. He was the associate of many noted men, including Sir Joseph Banks, Joseph Priestley and Erasmus Darwin, and it is interesting to recall that one of his daughters was the mother of the great naturalist Charles Darwin. Amongst his many other activities, Wedgwood was probably the first to make and show how to obtain correct determinations of high temperatures. His first paper was read before the Royal Society, being communicated in 1782 through Sir Joseph Banks. This description of his researches led to his receiving the honour of being elected as a Fellow of the Royal Society.

Dr. Helenus Scott (1760–1821)

Dr. Helenus Scott entered the medical service of the East India Company, and was for thirty years in India, chiefly in the Bombay Presidency, where he was the first member of the Medical Board; he afterwards returned to England, practising as a physician in Russell Square, where Stodart resided. Dr. Scott is associated with the subject of this book by the fact that he sent to the then

President of the Royal Society, Sir Joseph Banks, specimens of native Indian steel or wootz. This material attracted a great deal of attention by reason of its peculiar properties. It was first investigated by Dr. George Pearson, F.R.S., in 1795, at the instance of Sir Joseph Banks, and later, in 1819, Faraday made an analysis of wootz. This may fairly be considered as the commencement of Faraday's work on steel and its alloys, and in his papers on alloys of steel, presented to the Royal Institution in 1820, also to the Royal Society in 1822, he refers to various attempts to make wootz by alloying.

Sir Joseph Banks, P.R.S. (1743–1820)

This famous English traveller and botanist, who did so much for the advancement of knowledge by the liberal expenditure of his wealth on voyages of discovery and other fruitful objects, was President of the Royal Society from 1778 until the time of his death in 1820. His scientific expedition to Newfoundland and Labrador in 1766, his voyage with Captain Cook to the Pacific Ocean, and his expedition to Iceland in 1772 all resulted in the collection of a vast amount of information, specially as he took with him many skilled assistants. As President of the Royal Society for forty-two years, he did much to advance science in this country and to promote international relations between scientists of different countries. It should also be added that the first meeting regarding the formation of the Royal Institution was held at the house of Sir Joseph Banks in 1799. He it was who received from Dr. Helenus Scott, of Bombay, specimens of Indian steel or wootz, and it was by his instrumentality that Dr. Pearson and other highly qualified persons investigated the nature and properties of this material, and thus helped to arouse Faraday's interest in the whole question of steel and its alloys.

Sir Joseph's laboratory, which was considered the richest of its kind, is still kept in a room at the British Museum, but his natural history collections have been transferred to South Kensington.

Dr. George Pearson, F.R.S. (1751–1828)

Born at Rotherham in the year 1751, George Pearson qualified as a medical practitioner, being awarded the degree M.D. in 1773. He was of lively temperament, an excellent lecturer and a "methodical, ingenious and trustworthy experimenter." He was elected a Fellow of the Royal Society in 1791, being described on his nomination paper as "George Pearson of Leicester Square, a

SIR JOSEPH BANKS, P.R.S.
1743–1820.

[*To face p.* 36.

PLATE VIII

George Pearson

M. D. F. R. S.

Born 1751: — Died 1828.

From the only known portrait and now in the possession of the Royal Society.

To face p. 37.]

gentleman well skilled in chemistry and in many branches of knowledge." For many years he was a member of the council of the Royal Society, and he read a number of important chemical papers, and was an early advocate of vaccine. One of the first to appreciate the theories of Lavoisier, he did much to spread them in England by translating in 1794 the *Nomenclature Chimique.*

At the instigation of Sir Joseph Banks, who was then President of the Royal Society, Pearson undertook the investigation of the nature and properties of wootz, in which work he was associated with James Stodart. Pearson's results were presented to the Royal Society in a paper which was published in the *Philosophical Transactions* for 1795 and, in the course of that paper, Pearson refers to the fact that Stodart forged a penknife from wootz, at the desire of Sir Joseph Banks, and found it to be superior for many purposes to any steel then used in this country.

Pearson's examination of wootz helped materially to increase the interest of others and, in due course, Faraday analysed wootz steel and attempted to imitate it by alloying. From various references in his (Faraday's) papers it appears that the problem of making wootz by alloying was one to which he devoted special attention in the course of his broader investigation of alloys of steels with a whole range of different elements.

James Stodart, F.R.S. (1760–1823)

In view of the special association of James Stodart with Michael Faraday in his researches on steel and alloys, it is desirable to learn as much as possible about him, if only to enable us to form a better idea of the extent to which Faraday himself contributed to the researches on steel alloys. The two famous papers on the subject to which full reference is made in pages 115 to 121 of this book, one presented to the Royal Institution in 1820, the other to the Royal Society in 1822, were both by "Stodart and Faraday," but there can be no doubt that the planning and the execution of the researches, as well as the writing of the papers, were almost, if not entirely, Faraday's work.

Stodart was a man of considerable scientific attainment, but in no respect did he ever reveal capabilities at all comparable with those of Faraday. He was a maker of surgical instruments, and had doubtless workmen of his own and a more or less extensive connection with steelmakers which proved useful to Faraday, but Stodart's connection with the steel alloy research was rather on the practical side of testing samples than in relation to the formulation of the research and the preparation of alloys. The priority

given to his name in the authorship of the papers was no doubt due to the fact that he was already an elderly man of established reputation, a Member of the Royal Institution and (in 1821) a Fellow of the Royal Society, whereas Faraday was then quite young, and had not yet been made Director of the Royal Institution Laboratory.

Stodart was sixty years of age when the Royal Institution paper was read in 1820, Faraday being then only twenty-nine years old. Stodart was elected a Fellow of the Royal Society in 1821, and Faraday in 1824, the same year in which he was appointed Director of the Royal Institution Laboratory.

It has been no easy matter to get together the desired information regarding James Stodart, as neither the Royal Society nor the Royal Institution possesses much information about him. However, when it seemed at one time that the search would be fruitless, the author found, to his great satisfaction, at the Library of the Guildhall, a copy of *The English Encyclopædia*, in which there is a most excellent article on Mr. James Stodart, F.R.S., evidently written by someone well acquainted with him and his work. From this and other sources the following information is presented, though unfortunately it has not been possible to obtain a portrait of Mr. Stodart, as the author has been able to do with most of the other individuals mentioned in the table of *Dramatis Personæ*.

The well-known collector Mr. G. H. Gabb is the fortunate possessor of a silver-mounted case of green shagreen containing a set of steel surgical instruments made by Stodart, regarding which he furnished the author with the following information. This set consists of two scalpels, three steel probes and two heavy forceps, the date of these being about 1800–1810. In the collection also was a pair of razors which belonged to one of Mr. Gabb's relatives stamped with the Crown and V.R., as well as the words "Concave Razor, Silver Steel," of about 1845 date. Faraday frequently states that razors were made from some of his steels. It is therefore possible that the above-mentioned razors were made from steel resulting from Stodart and Faraday's researches. In any case, they represent the type of steel used at that time for razors. The author was able to purchase one of these, tests on which are fully described on p. 239.

Two of Stodart's trade cards may be seen at the British Museum. The earliest, of date about 1800, is inscribed:

"J. Stodart, Surgeon's Instrument maker and Cutler. No. 401, Strand, nearly opposite the Adelphi. Fine Razors, Varieties of Knives, Scissors, etc., Tempered by the Thermometer."

This reveals an early application of the thermometer for tempering, and suggests that Faraday may have learnt from Stodart that appreciation of the importance of accurate heat treatment which he emphasises in his writings.

Stodart's later trade card, probably of about 1820, reads :

> " J. Stodart, at 401, Strand, London, Surgeon's Instruments, Razors and other Cutlery made from उम (wootz) a Steel from India, preferred by Mr. S. to the best steel in Europe after years of comparative trial."

This card, too, is instructive, for it shows the high estimation in which wootz was held at that time.

From the directories of those days, it appears that J. Stodart carried on the business of " Surgeon's Instrument Maker " at 401, Strand from before 1800 until 1821 (two years before his death), when the name was changed to W. Stodart, and continued until about 1835.

A search through the early rate books at Westminster Town Hall reveals the fact that " Jas. Stodart " became tenant of 401, Strand, London, in the year 1787, at a rental of £35 per annum, with rates £4 7*s*. 6*d*. (happy man !). The rental of all the houses in the Strand appears to have averaged £35 to £45 at that time. Nowadays the charge for premises of the same site area is more like £2,000 per annum, with half as much again for rates.

The old house at 401, Strand was apparently rebuilt about thirty-five years ago. It seems at one time to have carried with it land extending back to Maiden Lane, so that in Stodart's time there would have been ample room for workshops.

The author is indebted to Mr. G. H. Gabb for interesting particulars concerning Stodart's business circumstances and, in reply to an enquiry as to the probability of Stodart's workshops being behind the shop in the Strand, Mr. Gabb wrote as follows :

> " Since I saw you I have in a leisurely way continued my researches about Stodart and am now able to say definitely that he began business at 401 Strand as early as 1792, and the business was carried on as ' J. Stodart ' until 1821, when it changed to ' W. Stodart,' and continued so till 1835, when the name became ' David Stodart,' and remained so till 1839, when apparently the business ceased to exist.
>
> " I may tell you that until recently I had an interest in a firm of instrument makers (Dring & Fage), who carried out the *whole* of their production at 145 Strand (*a few doors from Somerset House*) from 1881 to 1901. Dring and Fage was founded in 1725, and still continues at 56, Stamford Street, and was always in the family until six years ago, when I sold it.

"Their production consisted of forging, grinding, brazing, plating, etc., and considerable wood working as we made all the gauging instruments for H.M. Customs, etc., so you need not hesitate to assume that Stodart did all his 'production' at 401 Strand as the rear of his premises ran into Maiden Lane, and as '401' is at the corner of Lumley Court it gave easy access to his works in the rear—and this was in 1822, a very different Strand from to-day or 1881–1901."

The minutes of the London Cutlers Company from 1770 to 1795 reveal no trace of Mr. James Stodart, so he was evidently not a member of this guild.

There appears to be little known about the early life of Mr. James Stodart, but at the time with which we are concerned he was "a maker of surgical instruments and superior articles of cutlery in London." He had earned for himself a reputation as a man of science, specially as regards its applications to his own business, "for he did not make philosophical researches though he became companion and friendly assistant to those who did."

The papers published by Stodart alone were few in number and of quite a different calibre from the two joint papers (Royal Institution, 1820, and Royal Society, 1822) by Stodart and Faraday; these papers, on the other hand, are couched precisely in Faraday's style, and there can be no reasonable doubt that he was mainly, if not entirely, responsible for their preparation. As might be expected, several of Stodart's writings were on practical matters more or less directly bearing upon his trade of cutler and surgical instrument maker. All his independent publications appear to have been contributions to *Nicholson's Journal of Natural Philosophy, Chemistry and the Arts*. Therein we find him writing, in 1802, On the Effects of Respiration of the Nitrous Oxide (*Nicholson's Journal*, I., 225–7); in 1804, on an Experiment to Imitate the Damascus Sword Blade (*Ibid.*, VII., 231–2); and in 1805, on the Precipitation of Platina as a Covering or Defence to Polished Steel, and also to Brass (*Ibid.*, XI., 117–9), and a Method of Gilding upon Steel by Immersion in a Liquid (*Ibid.*, XI., 215–6). Then, for a period of fifteen years, there is no trace of any paper being published by Stodart until we come to those in which he appears as joint author with Faraday in 1820 and 1822.

An interesting reference to Stodart is to be found in *Metals and Alloys* (1857), where the following words appear on p. 379, referring to heating steel in the lead bath: "Mr. Stodart, cutler and surgeon's instrument maker, more than forty years ago (*i.e.*, certainly not later than 1817) tells us that he has lately tried this method and found it to be a great acquisition to the art." Evidently Stodart, with his tempering by thermometer, his use of

the lead bath for heating steel, and his years of comparative trials between wootz and other steels, was a man keenly interested in the progress of his craft and seeking continually for improvements. Our respect for him increases greatly as we piece together the rather fragmentary records available.

A striking instance of his enthusiasm is to be found in his letter describing the effects of breathing nitrous oxide, published in *Nicholson's Journal,* Vol. I., 1802. Following the discovery by Sir Humphry Davy, on April 9th, 1799, that pure nitrous oxide or " laughing gas " was respirable, it became quite a fashionable craze to take a dose of this gas. Soon after Davy was appointed Director of the Royal Institution Laboratory and lecturer in chemistry, in 1801, Stodart had an opportunity of gratifying his curiosity, which had been whetted by all that he had read and heard concerning this strange gas. Writing to Mr. Nicholson from the Strand, under date February 19th, 1802, Stodart tells that he first had an opportunity of breathing nitrous oxide in June, 1801, when in the company of Mr. (afterwards Sir Humphry) Davy in the laboratory of the Royal Institution. A little nervous at the first trial, Stodart soon became bold, not to say rash. Within a period of ten days or so he had taken repeated doses of four or six quarts of the gas at a time, experiencing pleasurable sensations, and apparently deriving subsequent benefit from the experiment. After a further dose on June 13th, however, he awakened with very alarming symptoms, and it took him several days to recover his accustomed strength and spirits. He does not appear ever to have indulged in experiments of this kind again, and, with the exception of his notes on the Damascus sword blade, the gilding of steel and the precipitation of platina, the author has been able to find no further publications bearing his name until the joint papers by Stodart and Faraday were published in 1820 and 1822.

Stodart participated actively in the investigation of the properties of wootz, at the request of Sir Joseph Banks, and he appears to have been specially successful in applying this material to the manufacture of surgical and other instruments in which great perfection and durability of edge were required.

Among other applications, Stodart forged the knife edges of Captain Katers' original invariable pendulum from a piece of wootz. His practical experience and skill in the working of steel were in many respects essential to Faraday's investigation of steel alloys, and there is little doubt that his death on September 11th, 1823, at the age of sixty-three years (Faraday being then thirty-one years of

age) may have been one of the factors causing Faraday to discontinue his work on steel.

As an indication of Stodart's practical and scientific knowledge, it may be mentioned that he had the distinction of correcting the great Sir Humphry Davy himself, who had united with Dr. Thomas Thomson in concluding that the change of colour produced by heat on the surface of polished steel probably did not depend on the oxidation of the metal. Stodart, who had made many accurate experiments on the tempering of steel and was familiar with the changes of colour and the temperatures at which they occur, sent various specimens to Davy indicating that the colour of the steel did not change if air was excluded. This led to further trials, which proved conclusively the correctness of Stodart's opinion that temper colours were a consequence of oxidation.

It is interesting to note that when Stodart was nominated for admission to the Royal Society in 1821, special attention was drawn to his work on alloy steels. His nomination paper reads as follows :

"Mr. James Stodart of Russell Square,
a gentleman well versed in various branches of natural philosophy and has particularly distinguished himself by interesting experiments on the alloys of steel, being desirous to become a Fellow of the R.S., we whose names are hereunto subscribed do of our own personal knowledge recommend him as worthy of that honour and likely to prove a useful Fellow Member.

"Th. Murdoch,
"Spencer,
"W. H. Wollaston,
"Thomas Harrison,
"J. Davy,
"Charles Wilkes,
"T. Chevalier.

"Balloted for and elected June, 1821."

It will be seen that Stodart's experiments on alloys of steel were advanced as a special reason for his election and, without wishing to under-estimate Stodart's qualifications, which were undoubtedly high, it may be claimed that Faraday's contribution to the joint research helped to secure for his senior the distinction which was awarded to Faraday himself three years later, in 1824.

"Mr. Stodart," says his biographer in *The English Encyclopœdia*, "was one of the earlier appreciators and friends of Michael Faraday, who, when chemical assistant in the Royal Institution, was engaged with him in a series of experiments on the alloys of steel, which were pursued for several years in the laboratory of that establishment, of which Mr. Stodart was an active member."

JAMES STODART, F.R.S.

1760—1823

Maker of Surgical Instruments.

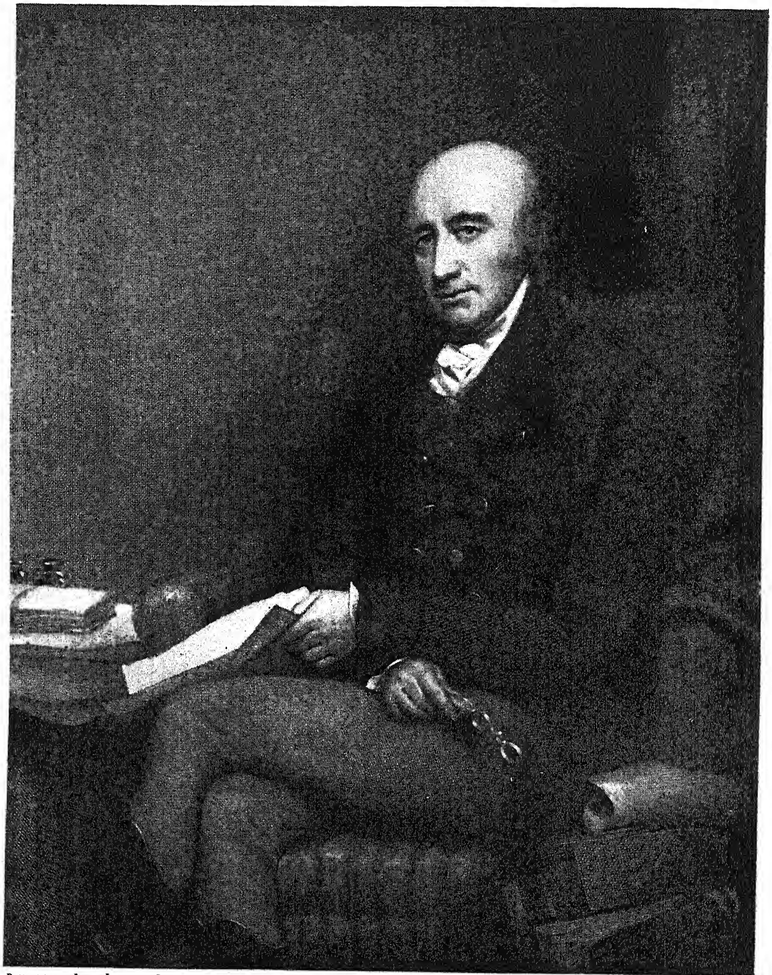
He was joint author with Faraday of the two papers, "Experiments on the Alloys of Steel, made with a View to its Improvement," read before the Royal Institution in 1820, *Q.J.S.*, Vol. IX., 319/330, and "On the Alloys of Steel," read before the Royal Society in 1822, *Phil. Trans.*, 21–3–1822, p. 252.

Mr. James Stodart also read papers alone "On the Effects of Respiration of the Nitrous Oxide," in 1802, *Nicholson Jnl.*, I., 225/7, "Account of an Experiment to Imitate the Damascus Sword Blades," in 1804, *Nicholson Jnl.*, VII., 231/2, "Method of Gilding upon Steel by Immersion in a Liquid," in 1805, *Nicholson Jnl.*, XI., 215/6, and "Precipitation of Platina as a Covering or Defence to Polished Steel, and also to Brass," in 1805, *Nicholson Jnl.*, XI., 117/9.

Although careful and extended search has been made at the British Museum, the National Portrait Gallery, the Royal Society, the Royal Institution, the leading sellers of engravings and portraits, also other likely sources, it has not been possible to find a portrait of Stodart. His signature, however, will be found in the list of *Dramatis Personæ* in this book.

Mr. Stodart resided in Russell Square, London, and his business house was at 401, Strand, with his workshop at the back.

[*To face p.* 42.



PAINTED BY JOHN JACKSON, R.A.. ENGRAVED BY WILLM SKELTON,

To His Royal Highness Prince Augustus Frederick Duke of Sussex. K. G. & T. G. C. H. &c. &c. &c. &c.
This Portrait of the late WILLIAM HYDE WOLLASTON, M.D. F.R.S. &c. &c. &c. *is with H. R. H's*
most gracious permission most respectfully inscribed,
By His Royal Highness's
most dutiful & obedient Servant,

Proof WILLM SKELTON

Published Novr 18th 1830 by W. Skelton, 1 Stafford Place, Pimlico.

DR. W. H. WOLLASTON, P.R.S.
1766–1828.

To face p. 43.]

In this respect, too, Stodart formed a link between Faraday and Sir Joseph Banks, for the specimen of Indian steel which Faraday analysed in 1819 was cut from one of the cakes which had been originally presented to Mr. Stodart by Sir Joseph Banks. Artificial wootz was made at an early stage in Stodart and Faraday's joint investigations, and the work then proceeded over a much wider field (as recounted in Chapter VI. of this book). Within a year of the publication of the Royal Society paper " On the Alloys of Steel," in 1822, Stodart died at Edinburgh on September 11th, 1823. As evidence of the friendly relations existing between the two men, he bequeathed a portion of his collection of philosophical apparatus to Faraday.

The death of Stodart at the comparatively early age of sixty-three years was specially unfortunate as regards the investigation of alloys of steel. As his biographer remarks: " The further improvements in the manufacture of steel in the direction they (Stodart and Faraday) had taken would appear to have been stopped by his demise." It is evident from the Royal Society paper of 1822 that the manufacture of the steel alloys was proceeding at Sheffield with encouraging results. The experiments had " excited a very considerable degree of interest both at home and abroad." Some commercial use was being made of the steel-silver alloy by at least one Sheffield firm, and the alloy of silver as well as that of platinum had been " to some considerable extent in use at His Majesty's Mint." At this critical stage Stodart died, and though he may have been, and probably was, the minor partner in respect of the scientific side of the work, he was an energetic and widely respected man in close contact with steelmakers and the cutlery trade and not tied down, as Faraday was, to work and responsibilities at the Royal Institution. True, Faraday continued his investigations for nearly another year, at any rate until the summer of 1824. He was fully capable of carrying on with the scientific and laboratory side of the work, but without access to forge, workshop and trade through his colleague further substantial advance must have been impossible. Neither then nor now could practical success with steel alloys be reached by laboratory work alone.

Dr. William Hyde Wollaston, P.R.S. (1766–1828)

In more than one place, Stodart and Faraday pay tribute to the important assistance received from Dr. Wollaston, specially in regard to the liberal supply of noble metals for use in the pre-

paration of alloys of steel. Thus, in their first paper * they say: "It is to Dr. Wollaston we are indebted, not only for suggesting the trial of rhodium, but also for a liberal supply of the metal, as well as much valuable information relative to fuel, crucibles, etc.; this liberality enables us to continue our experiments on this alloy." Evidently this liberality was continued on an increasing scale, for in their second paper † Stodart and Faraday say: "We are happy to acknowledge the obligations due from us to Dr. Wollaston, whose assistance we experienced in every stage of our progress, and by whom we were furnished with all the scarce and valuable metals; and that with a liberality which enabled us to transfer our operations from the laboratory of the chemist to the furnace of the maker of cast steel." To supply precious metals on such a scale as this was valuable assistance indeed, and it is of more than passing interest to recall some further particulars of this broad-minded and generous scientist who contributed so substantially to the success of Faraday's work on steel alloys.

Born at East Dereham, Norfolk, on August 6th, 1766, W. H. Wollaston was educated at Charterhouse and Caius College, Cambridge. He qualified as a physician, and practised successively in Huntingdon, Bury St. Edmunds and London during the period 1789–1800. Then, at the age of thirty-four, he retired from the practice of medicine mainly, it is believed, on account of his sensitiveness and the "mental flagellation called anxiety" induced by his too keen susceptibility to the sufferings of patients. From his youth Wollaston had been keenly interested in scientific studies, and he possessed a genius for precise observation and delicate manipulation which enabled him to make many important discoveries and inventions. Combined with these he had practical and commercial instincts which enabled him to turn his scientific achievements to good account. Without abandoning "the character of a professional man and a master manufacturer," and while "always maintaining the position of a gentleman," he was able to amass a considerable fortune by his discoveries and inventions. At the same time, he contributed generously to the work of others, as witness the quantities of precious metals he supplied to Faraday, and the funds which he placed at the disposal of the Geological Society and the Royal Society for the promotion of research.

* "Experiments on the Alloys of Steel, made with a view to its Improvement," by Stodart and Faraday. *Quarterly Journal of Science*, IX., p. 319.

† "On the Alloys of Steel," by Stodart and Faraday. *Phil. Trans.*, 21–3–1822, p. 252; *Phil. Mag.*, Vol. LX., July–August, 1822, p. 363.

While still at Cambridge, Wollaston made friends with John Brinkley, the Astronomer Royal for Ireland, and with John Pond, and studied astronomy under their guidance. In 1793, at the age of twenty-seven, he was elected a Fellow of the Royal Society, among the signatories of his papers being William Heberden the elder, the Hon. Henry Cavendish and Sir William Herschel. On retiring from medicine in 1800, Wollaston applied himself energetically to studies in physics, chemistry and botany, and in 1801 he established himself in Buckingham Street, Fitzroy Square, with a laboratory, which he kept strictly private. There were good reasons for this secrecy, for he soon perfected a means of making platinum malleable, and from the sale of the prepared metal, and by supervising the construction of vessels therefrom for chemical manufacture, he acquired a fortune of some £30,000. His accuracy of manipulation and observation led him to discover palladium and rhodium in platinum ores, but, with characteristic caution, he declined to identify himself with these important discoveries until their veracity had been established beyond all doubt.

There were striking differences of temperament and attainments between Wollaston and his friend Sir Humphry Davy. These are clearly and concisely depicted in *The Life of Davy*, by J. A. Paris, who says that the animating principle of Davy's mind was a powerful imagination, generalising phenomena and casting them into new combinations, whereas the striking characteristic of Wollaston's genius was an almost superhuman perception of minute detail. Davy was ever imagining something greater than he knew; Wollaston always knew something more than he acknowledged. In Wollaston the predominant principle was to avoid error; in Davy it was the desire to discover truth. Each attained similar ends, but by different methods and on different planes. Davy's separation of the alkaline metals was "the product of a comprehensive investigation which had developed a new order of principles"; the detection of palladium and rhodium by Wollaston was "the reward of delicate manipulation and microscopic scrutiny."

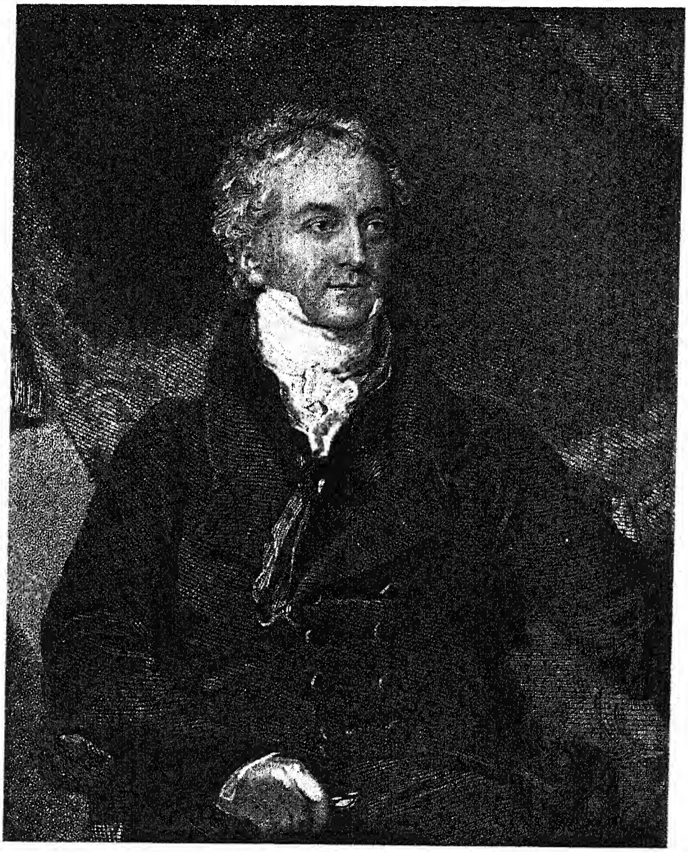
In his day, Wollaston was rightly accounted one of the foremost scientists in Europe. He was awarded the Copley medal in 1802, was Secretary of the Royal Society from 1804 to 1816, was later Vice-President on many occasions; also elected President on June 29th, 1820, occupying this position until November 30th in the same year; he might have been President in succession to Sir Joseph Banks, but chivalrously stood down in favour of Sir

Humphry Davy. Altogether Wollaston published some fifty-six papers, mostly before the Royal Society, on such diverse subjects as pathology, physiology, chemistry, optics, mineralogy, crystallography, astronomy, electricity, mechanics and botany. All his writings are characterised by a commendable clarity and brevity of expression. He took a leading part in clarifying the theories of chemical action, he invented many valuable optical instruments and devices, and it was he who suggested the " imperial gallon " (containing 10 lb. of water at a stated temperature) that was adopted by the Weights and Measures Act, 1824. Shortly before his death he recorded for publication his method of rendering platinum malleable, a successful process which he had hitherto kept secret. This was given in his Bakerian Lecture " On a Method of Rendering Platina Malleable," read before the Royal Society on November 20th, 1828.

Though he died at the early age of sixty years and did not embark seriously on his chemical, optical and other investigations until after his retirement from medical practice, Wollaston crowded an immense amount of valuable work into the last twenty-six years of his life. Of him it may truly be said that he lived respected and died regretted, and Faraday in particular pays tribute to the generous assistance which he gave to the researches on steel alloys.

William Hasledine Pepys, F.R.S. (1775–1856)

Mr. Pepys, who is less well known than he deserves to be, was born in London, in 1775, the son of a cutler and maker of surgical instruments. Apparently he followed his father's business, at any rate for a time, but he later acquired a high reputation as an instrument maker. He had remarkable skill and ingenuity in the construction of apparatus which contributed materially to the progress of chemical science for some thirty years or more. He supervised the construction of the powerful voltaic battery of 2,000 double plates for the Royal Institution laboratory and helped Davy in some of his electromagnetic investigations. In addition, he conducted researches on respiration, in conjunction with William Allen ; he published many papers ; and he was one of the founders of the Askesian Society (1796), one of the managers of the London Institution (1807), and later honorary secretary of that body (1821). He was elected Fellow of the Royal Society in 1808. Among his works are an analysis of Shetland iron and an interesting collection of MS. papers relating to the Royal Institution, now in the British Museum library.



Dr. Thomas Young, F.R.S.
1773–1829.

[To face p. 46.

WILLIAM HASELDINE PEPYS, F.R.S.
1775–1856.

To face p. 47.]

Thus Mr. Pepys, like his fellow-tradesman, James Stodart, acquired considerable distinction as a man of science, but, says the biographer of Stodart in *The English Encyclopædia* (1857), "it is a remarkable illustration of the manner in which intellectual endowments are distributed among different minds that Mr. Pepys, who also had an opportunity of making himself acquainted with wootz, though possessing equal professional skill and probably greater scientific qualifications, failed to recognise its superiority."

Be that as it may, on the other hand, much credit is due to Pepys for his ingenious experiment on the "steelification" of iron by diamond powder.* By heating electrically a wire of pure soft iron, containing a pinch of diamond powder in a notch, he proved that the iron was converted into blistered steel where it had been in contact with the diamond, the diamond itself disappearing in the course of the experiment. Further reference to this important experiment is made on p. 130.

Pepys was one of those with whom Sir Humphry Davy discussed Faraday's letter of application for employment at the Royal Institution in 1813, and it is evident that Faraday and Pepys were subsequently brought together on various investigations, for Davy records Stodart's assistance with that of Pepys, Allen and Faraday in the experiments he made at the Royal Institution and the London Institution on the magnetic phenomena produced by electricity. The paper describing this work forms part of the *Philosophical Transactions* for February, 1821.

Four razors bearing the name of Pepys have been preserved at the Royal Institution and, by the courtesy of the Managers, the author has been permitted to subject one of these to an examination, the results of which are given on p. 241 of this book.

DR. JOHN GEORGE CHILDREN, F.R.S. (1777–1852)

Born on May 18th, 1777, at Ferox Hall, Tonbridge, and educated at the Tonbridge Grammar School, Eton, and Queens' College, Cambridge, Dr. Children was a widely travelled man of great and varied attainments. Originally intended for the Church, the early death of his wife led him to travel in Southern Europe and the United States. On his return he devoted himself to scientific pursuits and, in the course of his studies of mineralogy, chemistry and galvanism, he became acquainted with Davy, Wollaston and other leading scientists of that day. He was elected a Fellow of the Royal Society in 1807, and soon afterwards performed some

* *Phil. Trans.*, 1815.

interesting investigations with very large voltaic batteries. After travelling in Spain, he resumed these investigations and published a further paper on the subject in 1815. During the period 1819–1822 he published translations first of Thernard's *Essay on Chemical Analysis*, and then of Berzelius' *Treatise on the Use of the Blowpipe* with additional experiments and notes. In 1824 he "derived considerable profit" by selling to several South American mining companies the right to use a new method which he had discovered for extracting silver from its ores without amalgamation. From 1816 to 1839 he was one of the Librarians of the British Museum in the Department of Antiquities (later Natural History), and during 1826–27 and from 1830 to 1837 he was Secretary to the Royal Society.

It was this eminent chemist who made a number of analyses for Faraday, as he acknowledged on several occasions, and no doubt Faraday owed a good deal of his early knowledge of chemical manipulation to the influence and assistance of Dr. Children.

Sir Humphry Davy, P.R.S. (1778–1829)

Notwithstanding a certain precipitancy of mind which sometimes led him to erroneous conclusions, and certain personal traits which sometimes led to offence, Humphry Davy was one of the most versatile and brilliant of English chemists and humanity owes much to his discoveries. Perhaps the best known of his many works was the invention of the miner's safety lamp, simple in itself but the means of saving innumerable lives. Apart, however, from this eminently practical invention, which is still often associated with his name and still used substantially as he devised it, Davy made many important discoveries in the field of chemistry. Even if he had no other claim to fame—and actually he had many—he would still be entitled to the enduring gratitude of the human race, for he was the man who gave Faraday his opportunity and, no doubt, in large measure his early inspiration. As related on page 11 of this book, Faraday secured his first position at the Royal Institution as the direct outcome of notes which he took and subsequently wrote up from four lectures delivered by Davy shortly before he resigned his position as lecturer in 1812. The fourth of the lectures was a very comprehensive and important one on Metals, and may well have had its influence in guiding Faraday towards his researches on steel alloys.

Born in Cornwall, in the year 1778, Davy appears to have shown no distinction at school, but at the age of sixteen he lost his father, and thereupon became apprenticed to an apothecary, and began to

DR. J. G. CHILDREN, F.R.S.
1777–1852.

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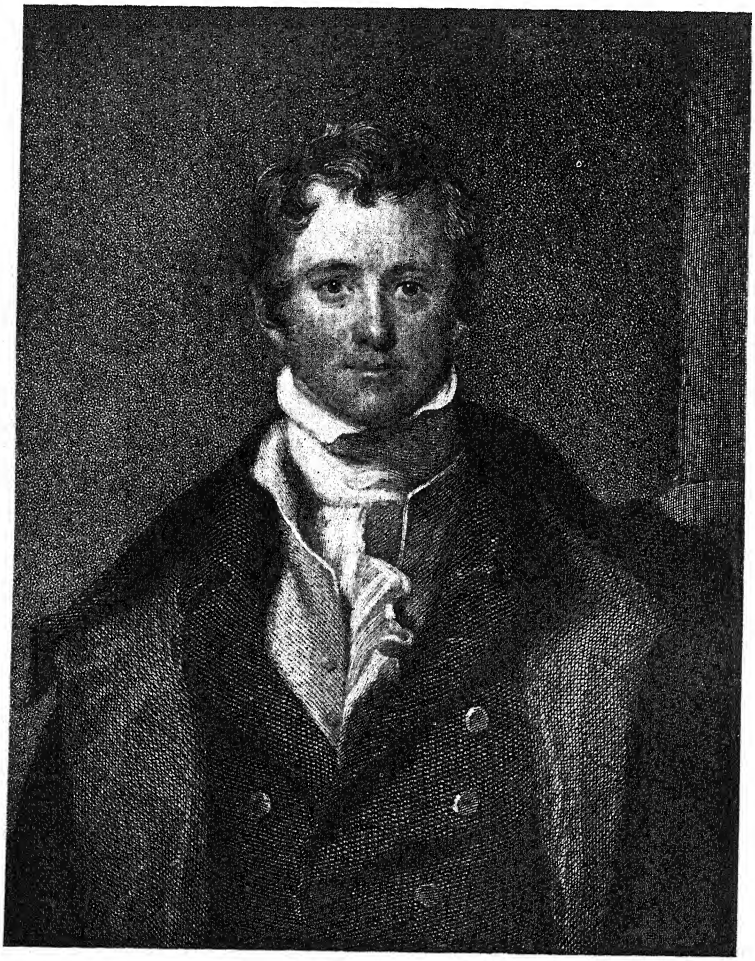


Sir Humphry Davy, P.R.S.
1778–1829.

To face p. 49.]

study in earnest, with a view to becoming a medical practitioner. Soon the range of his studies, together with his brilliant capabilities, attracted favourable notice, and by the time he was twenty years of age he was superintendent of the Medical Pneumatic Institution at Bristol. Within a few months he had attracted widespread attention by his researches on nitrous oxide, and this led to his being appointed lecturer in chemistry and director of the laboratory in the newly established Royal Institution. In May, 1802, he was given the rank of professor, and thereafter his rise to fame was rapid. As a lecturer he was remarkably popular, and the theatre of the Royal Institution was crowded to the full to hear him and to witness his many ingenious experiments. He was elected a Fellow of the Royal Society in 1803, knighted in 1812, created a baronet in 1818, chosen as President of the Royal Society in 1820, and died at Geneva in 1829, aged only fifty-one years.

The range of his investigations was immense, and this is not the place to attempt a comprehensive survey of them, particularly as they are already treated fully in several excellent works of biography. Davy's main researches at the Royal Institution were those relating to electrochemistry. In this field he added greatly to previous knowledge and laid some of the foundations of modern electrolytic industries, his work being brilliantly amplified by Faraday in later years. His success in the electrolytic preparation of potassium and sodium (1807) brought him international recognition, and his reputation was further enhanced by his continued investigations in electrochemistry and concerning the nature and properties of various elements and compounds. Davy made known his discovery of the alkaline metals in a paper read before the Royal Society in 1807. By aid of electrolysis he decomposed potash and soda, thus obtaining the metals potassium and sodium. In recognition of these important discoveries, the French Academy awarded him the prize of 50,000 francs offered by the Emperor Napoleon for researches in electricity. Davy did not succeed in producing aluminium by electrolysis, but this was accomplished later, and to-day it can truly be said that vast electrochemical industries are founded largely on Davy's work.

Following upon the famous Continental tour of 1813–1815, referred to on pages 11 and 12, on which he was accompanied by Faraday as "assistant in experiments and writings"—a tour which was of incalculable value to Faraday—Davy tackled and solved the problem of devising a safety lamp for miners. Incidentally, he laid down principles which are now applied in the

construction of "flame-proof" enclosures of electric motors and similar apparatus for use in explosive atmospheres. Though he gave up his position as lecturer at the Royal Institution in 1812, Davy was re-elected professor of chemistry a few months later. He was appointed Honorary Professor of Chemistry in 1813, the year in which he commenced his Continental tour, and this appointment he held until the year 1823.

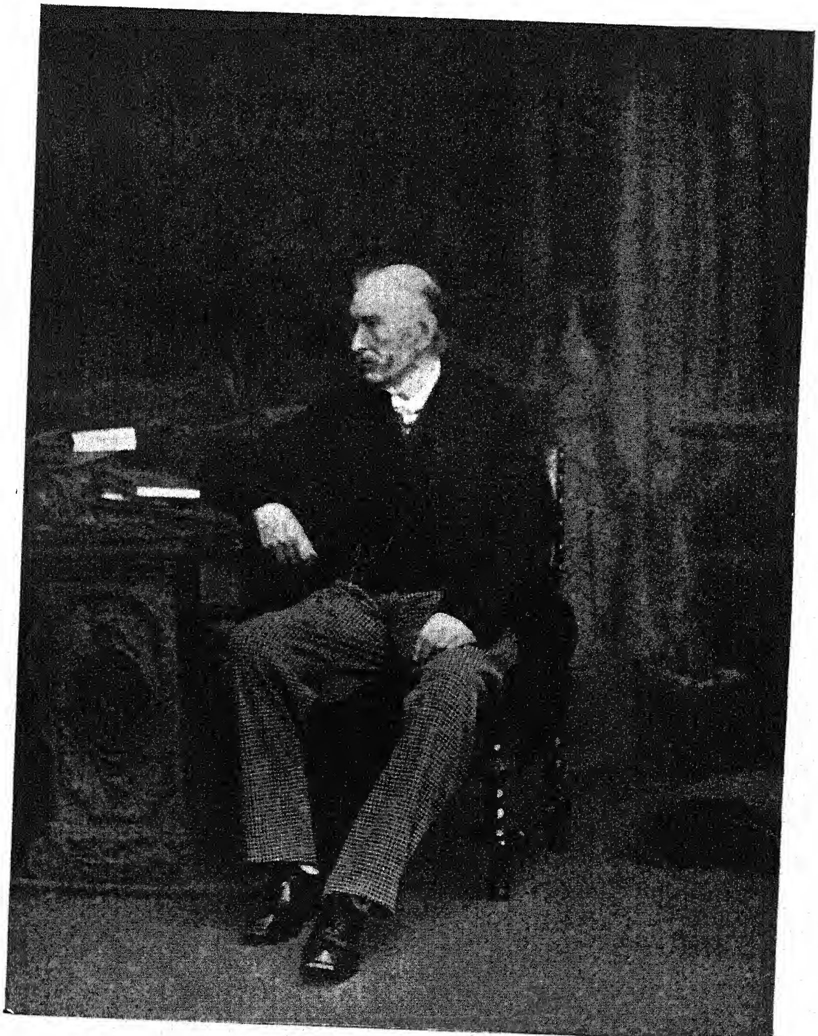
His later work during the period 1818–1825 included the examination of the papyri of Herculaneum, various electrical experiments, consideration of the applications of liquefied gases, and attempts to preserve the copper sheathing of ship hulls. From about the year 1823 his health began to fail, and he died six years later after a meteoric career of remarkable brilliance.

Dr. Samuel Hunter Christie, F.R.S. (1784–1865)

This well-known mathematician and physicist was a son of James Christie the auctioneer, who founded the world-famous "Christies." In 1806, at the age of twenty-two years, Samuel Hunter Christie was appointed third mathematical assistant at the Royal Military Academy, Woolwich, and he was subsequently promoted to second mathematical assistant in 1821, and to the professorship of mathematics in 1838. His activities also extended far beyond the range of mathematics. He was elected a Fellow of the Royal Society in 1826, and was Secretary of that body from 1837 to 1854. Altogether, he contributed fourteen papers to the *Philosophical Transactions* of the Royal Society, and in 1833 his paper on the magnetic-electric conductivity of metals was the Bakerian Lecture for that year. His work contributed materially to the advance of magnetic science, and it is interesting to recall that he was the actual inventor, in 1833, of the invaluable electrical measuring device commonly known as the "Wheatstone Bridge." In this and other directions, Christie did much to facilitate quantitative electrical and magnetic measurements, the need for which was much enhanced by Faraday's discoveries and the developments to which they led.

In a special note in his diary under date June 28th, 1824, which is reproduced on p. 125, Faraday refers to the preparation of a nickel steel alloy "for Mr. Christie." In view of the active interest of Dr. S. H. Christie, F.R.S., at the Royal Military Academy, Woolwich, in magnetic investigations, there can be little doubt that Faraday prepared this material for his friend's experiments.

In his Bakerian Lecture Dr. Christie made the following



DR. SAMUEL HUNTER CHRISTIE, F.R.S.
1784–1865.

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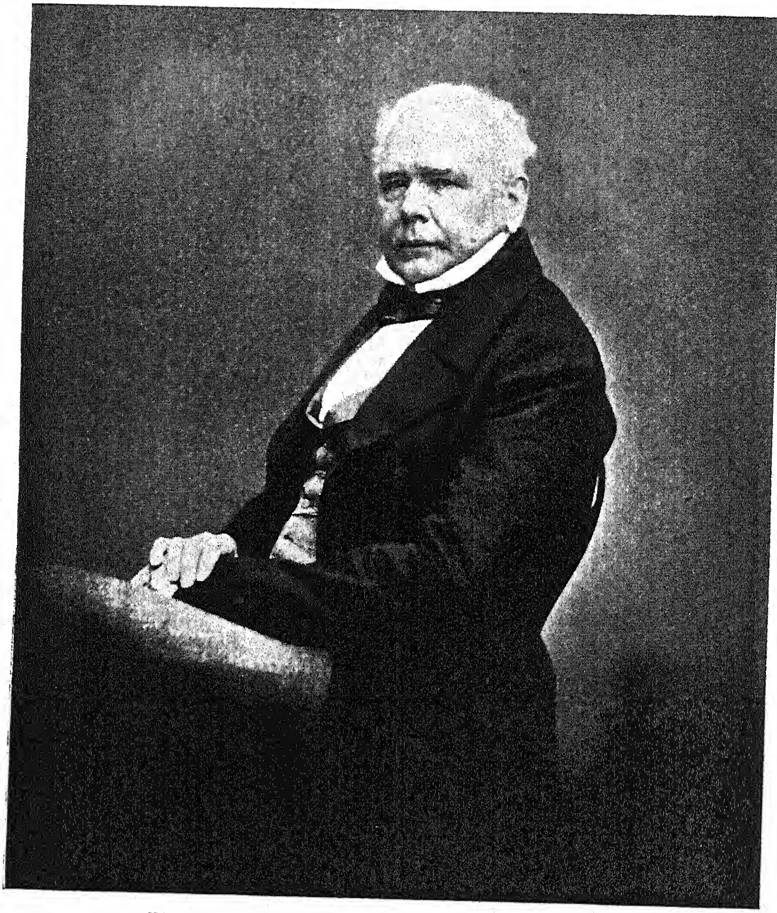

PROFESSOR WILLIAM THOMAS BRANDE, F.R.S.
1788–1866.

To face p. 51.]

interesting statement in relation to the great work of Faraday and how important it was regarded even at that time (February, 1832) :—

"Mr. Faraday's highly interesting paper entitled 'Experimental Research in Electricity' having been referred to me, to review on, by the President and Council of this Society, I instantly entered minutely into all the experiments and conclusions of the author and the more so after I had had the advantage of witnessing many of the most important of these experiments. It is foreign to my present purpose to discant upon the value of Mr. Faraday's discovery or the merits of his communication, the President and Council have marked their opinion of this by the award of the Copley Medal to him, and to say that no one could concur more closely than I do in the propriety of the award."

PROFESSOR WILLIAM THOMAS BRANDE, F.R.S. (1788–1866)

Though, like Davy, he was originally apprenticed to an apothecary and intended for the profession of medicine, William Thomas Brande was so keenly interested in chemistry and studied this subject to such good purpose in his leisure hours that he was appointed Professor of Chemistry to the Apothecaries' Society in 1812, at the age of twenty-four years. It should be mentioned that his training in chemistry was under Dr. George Pearson, F.R.S., who was concerned with wootz steel. Shortly afterwards he delivered a series of lectures in place of Sir Humphry Davy, whom he succeeded as Professor of Chemistry at the Royal Institution in 1813. He worked at the Royal Institution until 1852 and was Honorary Professor from 1852 to 1856. He often helped Faraday, not merely by affording instruction and advice during his younger days, but also by consultation and in other ways when Faraday himself had become a chemist of established international reputation. Brande's *Manual of Chemistry*, first published in 1819, was a recognised text-book in its day; a later edition, published in 1841, contained over 1,400 pages. Its author was undoubtedly one of the leaders in the chemical field at that time. As an instance of the close relations that existed between Brande and Faraday, it may be recalled that Brande says, in the Preface of his famous book : "Much of this work has been written in the Laboratory . . . where I have uniformly received the active and able assistance of Mr. M. Faraday, whose accuracy and skill as an operator have proved of essential service in all my proceedings."

When Faraday accompanied Davy on his Continental tour he had to resign his position at the Royal Institution, and it was at the suggestion of Professor Brande, at a meeting of the managers

on May 15th, 1815, that he was reappointed, at a salary of thirty shillings a week, on his return in 1815. Faraday was engaged as assistant in the laboratory and mineralogical section and superintendent of the apparatus under the direction of Professor Brande, and next year he was granted an increase in salary to £100 per annum in consideration of the additional duties imposed upon him by the lectures of that professor. In 1819, Brande obtained additional accommodation for Faraday and, in 1821, Faraday was appointed superintendent of the house and laboratory in the absence of Professor Brande. From this it is clear that at any rate the first group of Faraday's investigations of steel alloys was conducted while he was assistant to Professor Brande.

While still a boy Brande became acquainted with a Mr. Charles Hatchett, who gave him much instruction in chemistry, mineralogical analysis, and the classification of ores and rocks. Mr. Hatchett also gave him specimens which formed the nucleus of the series used in later years for the lectures and classes of the Royal Institution.

In connection with our present investigation it is specially interesting to recall that Professor Brande was consulted by the Government, in 1823, on the manufacture of iron and steel with a view to obtaining better material for the dies used to strike coinage. For many years, too, he was superintendent of the die department, and in 1854 he was appointed chief officer of the coinage department at the Mint. The fact that Brande was consulted by the Government at a date when his assistant Faraday was still engaged on his researches on steel alloys leaves no doubt that Faraday must have received valuable counsel and advice from his chief. It is highly probable that Faraday's reference to the trials of certain of his alloys at the Mint, already mentioned on page 43, alluded to the problem of obtaining better and more durable dies, and it is more than likely that these trials were made at the instance of Professor Brande, who, whilst he did not make any great discoveries, was nevertheless a man of the highest attainments and reputation. Moreover, he performed a vast amount of useful work, the results of which were published in some twenty-seven papers presented to the Royal Society and in various scientific journals during a period of forty years.

Sergeant Anderson (1790–1866)

The "faithful Anderson," who came to help Faraday in 1827, was his zealous and valued assistant for many years, and the relations between the two men afford a happy example of perfect

SERGEANT ANDERSON.
1790–1866.

[*To face p.* 52.

confidence and mutual trust. It is said that it was hardly necessary for them to speak as they understood each other's thoughts. Anderson was proud and happy to be in the service of a master whose discoveries were so numerous and brilliant, and Michael Faraday was no less appreciative of the sterling qualities of an assistant so much after his own heart.

It is related in Sir Henry Roscoe's book on Faraday's life and work that, on one occasion, Faraday ordered "the faithful Anderson" to stir a certain chemical preparation until his return, which normally would have been an hour or so later. For some reason, however, Faraday did not return to the laboratory that evening, with the result that Anderson was found next morning still patiently stirring the pot.

Though he was probably able to contribute very little in the way of original thought and observation, it is evident that Anderson greatly helped Faraday in his labours by giving that implicit obedience and devoted service which count for so much in any walk of life, and certainly not least in the long sequence of careful operations needed to bring any scientific work to a successful conclusion.

It was Anderson, too, who greatly helped in looking after the glass researches carried out at the Royal Institution and elsewhere by Faraday in the years 1826 to 1829.

Faraday, in a letter under date February 3rd, 1865, described his faithful assistant in the following words, which show the intimate relationship with his assistant:

"Anderson came to assist in the glass-house for the service of science in September, 1827, where he remained working until about 1830.

"Then for a while he was retained by myself until in 1832 he was in the service of the Royal Institution, and paid by it.

"From that time to the present he has remained with that body, and has obtained their constant approbation.

"Mr. Anderson still remains with us, and is in character what he has ever been.

"He and I are companions in years, in work, and in the Royal Institution.

"Mr. Anderson was 75 years of age on 12th of last month.

"He is a widower, but has a daughter to keep his house for him.

"We wish him not to come to the Royal Institution save when he is well enough to make it a pleasure, but he seems to be happy being so employed."

Mrs. Jane Marcet (1769–1858)

Mrs. Jane Marcet was born in 1769, living eighty-nine years, and was the wife of Dr. Alexander J. G. Marcet, Honorary Professor of Chemistry at Geneva.

Her son, Mr. Francis Marcet, was elected F.R.S. in 1864, and wrote several papers with Professor A. A. de la Rive, F.R.S.

Faraday repeatedly spoke of her with gratitude as having greatly assisted and influenced him by her famous book, *Conversations on Chemistry*, 1806, and other productions.

In a letter to Professor A. A. de la Rive he said: "When I questioned Mrs. Marcet's book by such little experiments as I could find means to perform, and found it true to the facts as I could understand them, I felt that I had got hold of an anchor in chemical knowledge, and clung fast to it. Thence my deep veneration for Mrs. Marcet: first, as one who had conferred great personal good and pleasure on me, and then as one able to convey the truth and principle of those boundless fields of knowledge which concern natural things, to the young, untaught, and inquiring mind."

Professor Charles Gaspard de la Rive (1770–1834)

Professor Gaspard de la Rive was a magistrate, physician and chemist studying medicine at Edinburgh, receiving the Doctorate in 1797, and also studied in London. He was made Honorary Professor of Pharmaceutical Chemistry at the University of Geneva, meeting Faraday there in the year 1815, and forming with him a close friendship extending over many years. It was to Professor Charles Gaspard de la Rive that Faraday addressed the important letters on "Steel and Alloys."

Professor Arthur Auguste de la Rive, F.R.S. (1801–1873)

The son of Professor C. Gaspard de la Rive, and a celebrated physicist. He studied physics and chemistry, occupying the Chair of Physics at the University of Geneva. When quite young he co-operated in the experiments of Ampère.

Like his father, he corresponded with Faraday for many years, and there was a close and lifelong friendship between them. Professor A. A. de la Rive was in 1864 elected one of the eight foreign Associates of the Académie des Sciences, Paris.

Dr. John Percy, F.R.S. (1817–1889)

This well-known metallurgist is of special interest in connection with the subject of this book. About twenty-six years younger than Faraday, he was still a child when the researches on "Steel and Alloys" were in progress at the Royal Institution. In later years, however, Percy became intimate with Faraday and in 1863 he asked Faraday the whereabouts of his specimens of alloy steels, doubtless with the intention of subjecting them to analysis and

PROFESSOR CHARLES GASPARD DE LA RIVE.
1770–1834.

[*To face p.* 54.

PLATE XIX

Professor Arthur-Auguste de la Rive, F.R.S.
1801–1873.

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incorporating further information concerning them in his famous treatise, *Iron and Steel.* As explained on p. 126, Faraday was by that time unable to remember what had happened to the specimens or where they might be found.

Apart from this unsuccessful attempt to obtain possession of Faraday's specimens for examination, Percy deserves specially to be mentioned in this book because of his great influence on the development of scientific metallurgy, during the period of nearly fifty years, from about 1840 until the time of his death.

From his early youth Percy was greatly interested in chemistry, and he had first desired to become a chemist. Yielding to his father's persuasion to graduate in medicine, he was appointed physician to the Queen's Hospital, Birmingham, in 1839. The various metal-working industries in that neighbourhood soon roused an interest in metallurgy, and after being elected a Fellow of the Royal Society in 1847, he published his invention of a new method of extracting silver from its ores in 1848. He was appointed, in 1851, lecturer on metallurgy at the Government School of Mines and of Science applied to the Arts, later known as the Royal School of Mines.

This post was subsequently made a professorship, and it is impossible to exaggerate the value of Percy's services during the period of some twenty-eight years from the date of his appointment until his resignation in 1879. During that period his pupils included famous metallurgists, and many metallurgical improvements were suggested by, or arose from, his work. Among these developments was the Thomas-Gilchrist process for making Bessemer steel from phosphoric ores.

In addition to his invaluable services as lecturer and teacher, Dr. Percy analysed many specimens of iron and steel collected by his friend Mr. S. H. Bakewell, and undertook "the first serious attempt at a survey of our national resources as regards ores of iron."

His classic work, *Iron and Steel,* the first modern work of its kind, contained some 3,500 pages of scientific description and discussion of metallurgical processes and problems.

A man of wide interests, including chemistry, medicine, botany, mineralogy, art, social and political problems, as well as metallurgy, Percy had many friends. He took an extensive interest in public affairs and was a member of several Government commissions. He was awarded the Bessemer Medal of the Iron and Steel Institute in 1876, and was President of that body in 1885–1886. He was awarded the Millar Prize of the Institution of Civil

Engineers in 1887, and received the Albert Medal of the Society of Arts on his death-bed, with the words, " My work is done."

The metallurgical specimens now preserved at South Kensington form an appropriate memorial to one who did so much to advance metallurgy.

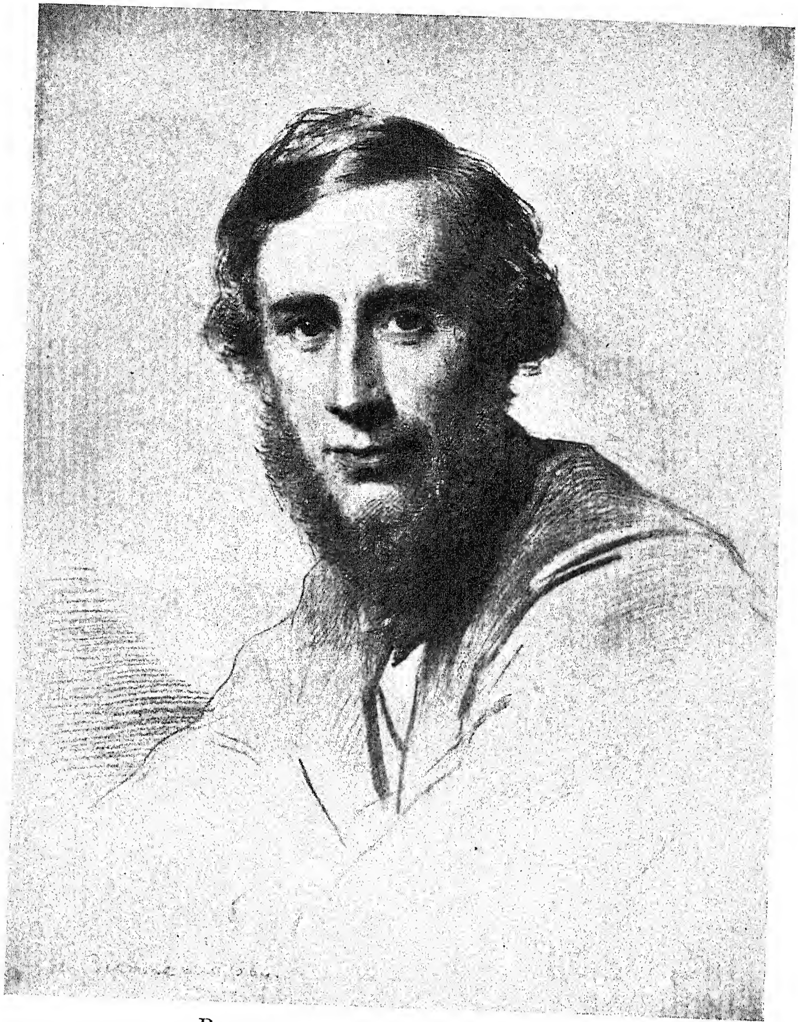
Professor John Tyndall, F.R.S. (1820–1893)

For many years the friend of Faraday, and ultimately his successor as Superintendent of the Royal Institution, Tyndall was one of the most brilliant and popular teachers of his generation. He carried on the work commenced by Faraday in this field with remarkable success, and his name is associated equally with those of Darwin and Huxley in the movement which brought science to its present relation with modern thought and life. Like Faraday himself, Tyndall had no advantages of birth or station, and he won his way to international recognition as one of the greatest physicists of the nineteenth century in the face of many difficulties. He first made Faraday's acquaintance in 1850 and he was appointed Professor of Natural Philosophy at the Royal Institution in 1853. In his disregard for personal gain, as well as by his widespread and beneficial influence on popular interest in science, Tyndall bore much resemblance to Faraday. He made many contributions to knowledge in the domain of physics, and it would be difficult to over-estimate his inspiring influence on all who came within his sphere.

The author is indebted to the Royal Society for several of the portraits and signatures shown in Plates III., VII., VIII., IX., XII.; to the Royal Institution for Plates V., XI., XIV., XVI., XXI.; to the Iron and Steel Institute for Plate XX.; to the University of Geneva for Plates XVIII., XIX., and XXV. The author begs to extend his best thanks to the Institutions for the kind permission given to present these portraits in this book.

Dr. John Percy, F.R.S.
1817–1889.

[*To face p.* 56.



PROFESSOR JOHN TYNDALL, F.R.S.
1820–1893.

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CHAPTER IV

EARLY WORKERS IN METALLURGY

Ages of Empiricism

In order that the merit of Faraday's work on "steel and alloys" may be fully appreciated, it is necessary to bear in mind not only the comparatively primitive resources then available in the way of scientific equipment, but also the extremely limited amount of scientific knowledge concerning the properties of iron and steel. Iron had been used for thousands of years in some parts of the world, and tools and weapons of carbon steel had been made with varying degrees of success by the smiths of many nations during the intervening period. Aristotle (384–322 B.C.) described the manufacture of Indian steel more than 2,000 years ago; the remarkable Iron Pillar of Delhi, analysed by the author and found to consist of nearly pure iron, was probably made about A.D. 300; and Chaucer, in his *Canterbury Tales* (1370), says of one of his characters: "A Shefeld thwytel bare he in his hose," showing that Sheffield cutlery was well known and esteemed nearly 600 years ago. The methods of the early workers in iron and steel were, however, quite empirical. By trial and error, they had found how to prepare and manipulate their materials, and this knowledge was handed down from father to son. In point of practical skill, the smiths of bygone ages were remarkably proficient; in fact, we should probably find it difficult to equal their results to-day if we were given only their materials and resources. They were, however, subject to the inevitable imitations of empiricism. Their methods were "rule of thumb," and they did not understand how or why their results were obtained. As a consequence it was difficult to distinguish between essentials and the flummery of mysterious quenching mixtures and other "secrets." Progress was necessarily difficult and slow, and all the greater credit is due to those who gradually built up the scientific knowledge which made possible such rapid advances in later years.

Early Workers

Up to the end of the eighteenth century and, indeed, during the first quarter of the nineteenth century—which brings us past the

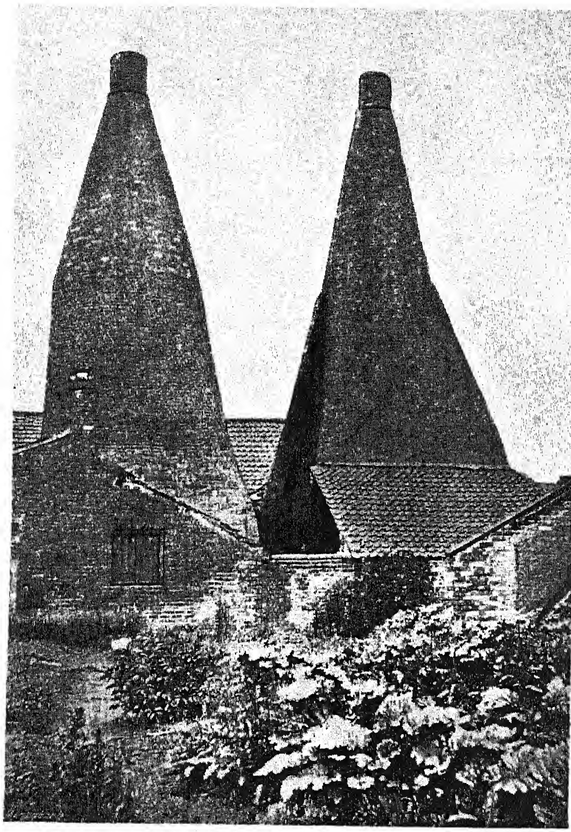
conclusion of Faraday's work on steel alloys, for his last-recorded experiments were made in 1824—the state of knowledge and practice in the iron and steel industry was very rudimentary. Perhaps the best means of illustrating this fact is by giving a list of those who may fairly be termed early workers in scientific metallurgy. It is surprising how comparatively recently many important discoveries and inventions have been made:

Dud Dudley (England, 1599–1684), first smelted iron with pit coal.
Simon Sturtevant (England), dealt in his *Metallica* with the use of coal for smelting (1612).
Sir John Pettus (England, 1613–1690), author of metallurgical works.
Andrew Yarranton (England, 1616–1684), introduced tin-plate manufacture.
Benjamin Huntsman (England, 1704–1776), manufacturer, perfected the manufacture of crucible cast steel.
Abraham Darby (England, 1711–1763), used coke for smelting.
Richard Kirwan (Ireland, 1733–1812), author, was one of the earliest writers on mineralogy.
Henry Cort (England, 1740–1800), engineer, introduced puddling and the use of grooved rolls.
William Reynolds (England, 1758–1803), patented (1799) the use of manganese oxide for steel manufacture.
David Mushet (England, 1772–1847), metallurgist, author, discovered black-band ore.
Robert Sterling (Scotland, 1790–1878), patented the regenerative principle (1817).
James Beaumont Neilson (Scotland, 1792–1865), invented the hot-blast (1828).

With the exception of crucible steel and shear steel, the ferrous metals in use at the time when Faraday carried out his researches on steel alloys were cast iron, wrought iron and puddled steel. At the time of its introduction, the crucible steel process invented by Benjamin Huntsman represented a great advance.

Benjamin Huntsman and Crucible Steel

In the author's papers to the American Institute of Mining Engineers on "Benjamin Huntsman, of Sheffield, the Inventor of Crucible Steel," read in February, 1894, and to the Iron and Steel Institute on "The Early History of Crucible Steel," August, 1894, there was included a Report on Huntsman's Cast Steel by Fourness and Ashworth, Engineers to their Royal Highnesses The Prince of Wales and Duke of Clarence. This report was written on March 28th, 1792, and describes the practice then prevailing, which was substantially the same as when Stodart and Faraday made their experiments in 1819–1824.



CEMENTATION FURNACES BUILT BY BENJAMIN HUNTSMAN ABOUT 1750.

(From a photograph prepared by the late Professor J. O. Arnold, F.R.S.)

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Curiously enough, some of the descriptive language employed by Fourness and Ashworth, relating to ordinary crucible cast steel of carbon type, is very similar to that which Faraday used in regard to his special alloys, for example: "It is calculated also to take the highest polish; therefore, for burnishing tools, and plates to beat or roll any kind of metal to a fine surface upon, it possesses a decided superiority." Again, "as a hint to opticians, it is probable this steel would admit of a polish sufficient for speculums; for mirrors it is particularly suitable. By a judicious workman, a plate of this steel can be laid to, and united firmly with any malleable iron or steel, of even an ordinary kind."

As a comparison, the Huntsman crucible cast steel referred to in the above-mentioned paper, "The Early History of Crucible Steel," was analysed by the author, with the following result:

C.	Si.	S.	P.	Mn.
1·40	0·17	0·47	0·017	0·18 per cent.

It will be seen that this steel is very much the same composition as that made by Faraday as shown in Group E.2 of Table V.

It will also be noticed how low the manganese percentage is, namely, 0·18 per cent., in this Huntsman steel. In all the steels made by Faraday there is even less of this element, in fact, in most cases only a trace of manganese is found. This point is again referred to later in this book.

Full credit is given generally to Benjamin Huntsman for his work in connection with crucible steel, specially as regards its production in this country. In support of this opinion, attention may be drawn to the remarkable statement by Dr. John Percy, F.R.S., President of the Iron and Steel Institute in 1885, one of the leading past authorities in metallurgy, who said:

> "Formerly, so far as I am aware, steel was never melted and cast after its production; and in only one instance, viz. that of wootz steel, was it ever molten during its production. Indeed, by the founding and casting of steel after its production its heterogeneousness is remedied, and ingots of the metal can be produced perfectly of uniform composition throughout; and for the practical solution of this important problem we are indebted to Benjamin Huntsman of Sheffield."

Also, as the author pointed out in his paper in 1894, already mentioned, an American journal of that date appropriately remarked:

> "Huntsman's patient efforts, at last rewarded with success, entitle him to an elevated niche among the heroes of industry. The invention of cast steel was second in importance to no previous event in the world's history, unless it may have been the invention of printing."

It is interesting to note that in 1787 a Sheffield directory gave the names of five firms producing crucible steel.

Early Workers in Alloy Steels

Though Faraday was the first to engage in anything in the nature of a preconceived research concerning a series of alloy steels, isolated alloys had been made before his time, and, strictly speaking, those who first discovered them, also the alloying elements, nickel, chromium, manganese, and others, are justly entitled to be considered early workers in the field of alloy steels. The first step towards making any alloy is to obtain the ingredients!

In his presidential address to the Iron and Steel Institute, in 1905, devoted to alloys of iron with other elements, the author gave credit to those early workers, Cronstedt, Scheele, Bergman, Rinman, Vauquelin and others, for their splendid work. Also, in his paper "The Development of Alloy Steels," presented to the Empire Mining and Metallurgical Congress, in 1925, the author reviewed the historical side of the subject before proceeding to a consideration of modern alloy steels. This is not the place in which to repeat such a survey in any considerable detail, but brief notes on the discovery and isolation of certain of the special elements used by Faraday will help the reader to a better appreciation of his work by showing that many of these elements had only been discovered a comparatively short time before he conceived the idea of investigating their alloys with both iron and steel.

Chromium was discovered by Louis Nicholas Vauquelin (France) in 1797.

Iridium was discovered by Smithson Tennant, in 1803, in the course of examining platinum ores.

Nickel.—Axel Frederic Cronstedt (Sweden) recorded in 1751 that he had extracted a new metal-nickel from its ore. This was confirmed in 1775 by Bergman, and subsequently the work was completed in 1803 by Richter in Berlin.

Palladium was discovered by W. H. Wollaston in 1803.

Platinum.—The so-called "native platinum," in reality a platinum ore, appears to have been known in South America long before it was noted by the Spanish explorer de la Torre during his travels with a French expedition, 1735–1748. Sir William Watson is believed to have been the first to subject the mineral to scientific examination and recognize it as a metal hitherto unknown (1750). Singularly enough its price in Faraday's time was only 20*s.* an ounce, whereas it is six to seven times as much now.

Rhodium was discovered in crude platinum ore by W. H. Wollaston in 1803.

Osmium was first obtained from platinum ores by Smithson Tennant in 1803.

Titanium was discovered by Martin Heinrich Klaproth (Germany) in 1794.

Silicon was isolated by Jons Jakob Berzelius (1779–1848), who was the originator of the theory of allotropy.

Aluminium.—Magraff, in 1754, showed that alumina was a metallic oxide, but Wöhler may be said to have been the true discoverer of the metal in 1827; whilst St. Claire Deville, in France, finally perfected the method upon which most of the modern work has been formed. Sir Humphry Davy, who produced sodium and potassium by electrolysis, did not succeed in separating aluminium by this method.

It is not always realised how much the subsequent progress of metallurgy was facilitated by the great work done in Sweden during the eighteenth century in the discovery and isolation of elements now used for alloy steels. Thus, apart from discoveries noted in the above list, which refers chiefly to the rarer metals used by Faraday, there was the discovery of cobalt by G. Brandt in 1733, and the discovery of manganese (1774), molybdenum and other elements by Karl Wilhelm Scheele (1742–1786). Rinman, about 1777, noticed that manganese deprived iron of its magnetic qualities. Uranium was discovered by Martin Heinrich Klaproth (Germany) in 1789; and the discovery of tungsten arose from the work of Bergman, in Sweden, and the brothers de Elhuyar, in Spain, in 1793. Tellurium was discovered by von Reichenbach in 1782.

From this brief survey it will be seen that Faraday's career was commenced at a date which was in a way opportune for research on alloys of steel, though no other investigator had realised the fact. Those who first isolated the rarer elements, generally with great difficulty and in very small quantities, would hardly have either the desire or the opportunity of alloying them with steel. By the time Faraday started work at the Royal Institution quite a number of these special elements were known, and supplies were available in larger quantities, particularly to Faraday, by the generosity of Dr. Wollaston. It was typical of the genius of Faraday that, seeking to make steels of special qualities, he should conceive the idea of making a whole series of alloys with these special elements, with a base of both wrought iron and steel.

Engineering and Metallurgical Developments of the Period 1820–1830

Though cast iron, wrought iron and puddled steel, with crucible cast steel for special purposes, met practically all requirements until about the middle of the nineteenth century, or even later, it

must not be overlooked that there was considerable activity in regard to engineering and metallurgical developments just about the time 1814–1824, representing the first phase of Faraday's busy life. This fact, which no doubt helped to arouse Faraday's interest in the question of improving the qualities of steel by alloying, is well illustrated by the frontispiece of an address which the author delivered to the Birmingham University Metallurgical Society on October 30th, 1923, dealing with the history and progress of metallurgical science and its influence upon modern engineering. This frontispiece, "The Temple of Science," which appeared in the *Engineers' and Mechanics' Encyclopædia,* published in 1835, represented allegorically the views prevailing in the nineteenth century with regard to science and its application. The illustration which is shown in Plate XXIII. claimed to comprehend "Practical illustrations of the machinery process employed in every description of manufacture of the British Empire." It showed, in the distance, the first locomotive drawing railway carriages, filled with coal or with the gentry of the day wearing "top hats." In the air is an airship or dirigible balloon; in the background a demonstration of the Torricellian vacuum; and an apparatus for the demonstration of static electricity. In the foreground can be seen allegorical figures examining plans of mechanical inventions, including a water-tube boiler and an engine with governor. The foreground is strewn with various tools and apparatus relating to engineering, metallurgy and chemistry.

The first locomotive made by George Stephenson in 1814 travelled at about six miles per hour, whilst the *Rocket,* in 1829, possessed what was then considered to be the high speed of twenty-five to thirty-five miles per hour. Nowadays man can travel at nearly ten times such speeds by land and air. The frontispiece of less than a century ago seems childish to-day, but it still serves a useful purpose by reminding us of some of the principal events at the dawn of the Scientific Age. It is only by discovering and applying the facts and principles of science in all its branches that we have been able to advance so rapidly and so far.

In order to show the extraordinary differences in the demand and use of iron and steel to-day as compared with that existing at the time when Faraday was making his experiments described in this book on "Steel and Alloys," the author has prepared the following statement which he trusts will be found of general interest. He prefaces the information now presented in this statement with the remark that in 1929 the world's output of steel was no less than about 4,000 times as much as in 1820.

THE TEMPLE OF SCIENCE.

This allegorical illustration, published in 1835, reflects the views prevailing in the early part of the nineteenth century with regard to science.

[*To face p.* 62.

The writer is indebted for preparing some of the data and checking over other parts to his friend, Mr. F. W. Harbord, C.B.E., President of the Iron and Steel Institute, 1927–1928, and who rendered so much help to his country on metallurgical matters during the Great War.

In the early part of the nineteenth century no reliable records were kept of the production of pig iron, wrought iron, or steel in Great Britain, and it is extremely difficult to arrive at the actual production. The main products were cast or pig iron, and wrought iron, as these were the principal materials used for structural purposes and the quantity of steel produced was very small. The famous tubular bridge over the Menai Straits was built mainly of wrought iron, although some parts were of cast iron.

In 1796 the production of pig iron in Great Britain was approximately 125,000 tons, in 1806 about 250,000 tons, and in 1824 about 450,000 tons, and also in this latter year about 200,000 tons of bar iron were produced. In comparison it may be interesting to add that in 1930 there was produced in Great Britain about 270,000 tons of puddled and scrap bar iron; finished wrought iron amounted to 210,000 tons; pig iron production was 6 million tons, with $5\frac{1}{2}$ million tons of finished steel.

In 1806 the average weekly output of a blast furnace was 21 tons of pig iron and in 1827 was only 35 tons. To-day a modern blast furnace will produce 1,000 tons per day and one furnace in America is said to be producing 1,500 tons of pig iron per day, or nearly as much in one day as was produced in 1820 in one year. So far as can be ascertained the total output of all the blast furnaces in Great Britain in 1820 was probably not more than 400,000 tons, and certainly did not exceed 420,000 tons per annum, this being equal to the output of one modern furnace of the latest type!

The annual production of wrought iron and steel is still more difficult to estimate, but probably the wrought iron produced in 1820 did not exceed 250,000 tons, and the output of steel of all kinds, including cemented bars made from imported iron, did not exceed 20,000 tons per annum, and the total production of the world was probably not more than 30,000 tons per annum. Mr. Henry Unwin of Sheffield, in giving evidence before a Committee of the House of Commons in 1846, stated that the total production of steel in England about that time was 40,000 tons, and about another 40,000 tons was produced in other countries, so that the total output of the world was then approximately 80,000 tons per annum. He added that for 1835 the production of steel in Sheffield

was 15,000 tons, so probably the tonnage produced in Sheffield in 1820 was not more than about 12,000 tons, and for the whole of England probably not more than 20,000 tons, chiefly of the " high carbon " type.

In 1929 the world's output of steel was nearly 120 million tons, or about 4,000 times as much as in 1820, of which about 5 million tons were alloy steels, approximately 70 per cent. being made in the United States. It must be remembered that prior to 1850 the whole of the steel was made by the crucible process, with the exception of a small quantity of shear steel made from cemented bars, and it was the invention of the Bessemer and Siemens processes, followed by the Thomas-Gilchrist basic process, which brought about the immense developments of the modern steel industry. This in turn made possible the great engineering progress in connection with railways, shipbuilding, bridge and building construction, electrical engineering, and a large number of other industries.

When the basic process was invented in 1879 the world's annual production of steel was 4 million tons; by 1929, a period of fifty years, it had increased to over 118 million tons, and of this immense production it is safe to say that approximately 90 per cent. was made by the basic process.

Thus in Faraday's time there was no special call for materials possessing the properties of modern steel alloys—the requirements and the environments were quite different from ours—but special steels are now absolutely essential. Without them it would be impossible to build the lighter, powerful and durable machinery and instruments of the thousand and one types which serve civilisation in innumerable ways.

It is unlikely that all the steels and alloys made by Faraday himself at the Royal Institution weighed as much as 1 cwt., and it is still more improbable that the total weight made to his instructions at Sheffield ever amounted to 1 ton. It was, in fact, an historic achievement that so many alloys were made at all, in however small quantities. The author's investigations show that none of Faraday's alloys was in any way comparable with modern alloys as regards practical utility, but the germ of the idea was there and the measure of the importance of Faraday's pioneer work in inaugurating research on alloy steels is to be found in the fact that the world's output of special steel products now runs into many millions of tons per annum, and in many cases one ton of alloy steel may be said to replace 15 or 20 tons of ordinary steel by increased durability and efficiency.

SIR HUMPHRY DAVY'S NOTES ON IRON

One of the most curious and convincing proofs of the very elementary state of scientific knowledge concerning iron at the time when Faraday embarked upon his researches is to be found in *The Collected Works of Sir Humphry Davy, Bart., Vol. IV., Elements of Chemical Philosophy.* This volume was first published in 1812, when Davy was about to retire from the Royal Institution. In an article in the *Quarterly Review*, No. 15, written by a very able judge, Dr. Thomas Young, the researches on which it was based were pronounced to be " more splendidly successful than any which have ever before illustrated the physical sciences in any of their departments," not even excepting the optics of Newton. With such words before us, concerning the collected works of one who is rightly regarded as among the most brilliant chemists of his time, we may fairly regard Davy's notes on " Iron or Ferrum " as indicative of the knowledge then prevailing. The following extracts are specially interesting :

" The soft iron employed in the useful arts is free from any alloy (it contains carbon ; according to Berzelius 0·5 per cent.), and therefore may be used for the purposes of chemistry.

" The malleability of iron, though considerable, is inferior to that of gold, silver and copper. Its ductility and tenacity are, however, greater ; it may be drawn into extremely fine wire, and a wire of 0·078 inch in diameter is capable of supporting 549·25 lb. It requires the highest heat of a wind furnace for its perfect fusion ; it is attracted by the magnet, and is capable of acquiring magnetism, though in its unalloyed state it retains it only for a very short time.

" Iron is capable of combining with carbon ; and *steel*, perhaps the most important substance employed in the useful arts, is one of the results of their combination.

" Steel is usually made by a process called cementation, which consists in keeping bars of iron in contact with powdered charcoal in a state of ignition for ten or twelve days, in earthen troughs or crucibles, the mouths of which are closed with clay.

" Cemented steel is made into the substance called *cast steel* by being fused in a close crucible with a mixture of powdered glass and charcoal.

" Steel is possessed of the power of receiving very different degrees of hardness by different applications of heat or cold. When it is heated to redness, and suffered to cool slowly, it is found very soft ; but if plunged into cold mercury or water, it acquires extreme hardness ; and by heating hard steel to different degrees, it receives different degrees of temper, from that which renders it proper for files to that which fits it for watch springs.

" In the process of tempering, the steel changes colour when exposed to the air. Between 430° and 450° Fahrenheit, according to Mr. Stodart, it assumes a pale yellowish tinge ; at 460° the colour is straw

yellow, and the metal is of the temper necessary for penknives, razors, and fine-edged tools. The colour gradually deepens as the temperature rises higher, and it passes through brown, red and purple to 580, when it becomes of uniform deep blue.*

"It is not easy to determine the exact quantity of carbon in steel, but it consists of several proportions of iron to one of carbonaceous matter. Different specimens of steel are said, on the authority of Bergman, Vauquelin and Mushet, to contain only from 1/140 to 1/60 of carbon.

"Plumbago, or *black lead*, as has been mentioned on p. 231, is a compound of carbon, with 1/25 its weight of iron. There is a substance formed in iron founderies called *kish*, of a brilliant appearance, usually in thin scales, analogous to plates of polished steel. It consists chiefly of carbonaceous matter united to iron, and a little magnesium.

"Iron is capable of combining with potassium and sodium; these alloys are more fusible and whiter than iron, and effervesce copiously in water. There is great reason to believe that alloys may be formed of iron and the metals of the earths.

"*Cast iron*, which is produced by fusing iron ores with pitcoal, during its conversion into malleable iron, affords about one-fourth of its weight of a glass, which consists of silex, alumine, lime, oxide of iron, and oxide of manganesum.

"In the process for reducing cast iron into malleable iron, called *blooming*, the iron, after being fused in a forge by a fire of charcoal, is hammered, whilst in a soft state, on an anvil by a large hammer worked by water; a vivid combustion, which seems to be connected with the formation of the glass and the oxides, takes place on the surface of the mass; that the earths are formed by the oxidation of metals combined in the cast iron, seems probable from the circumstances of the combustion; and the idea is confirmed by the distinct metallic character of cast iron; it is white, crystallized, and has all the appearances of a perfect alloy.

"Manganesum forms very readily binary combinations with iron; the alloys have a white colour, and are very brittle. Iron likewise combines with tin. By fusing the two metals together Bergman obtained two alloys; the first containing twenty-one parts of tin and one part of iron, the second two parts of tin and one of iron. The first was very malleable, harder than tin, and not so brilliant; the second scarcely malleable, and very hard."

These extracts indicate the state of knowledge, or rather the lack of knowledge, concerning the world's most important metal at the time when Michael Faraday foresaw the possibilities of alloy steels and made a valiant attempt to give them practical effect.

* Originally Davy said: "These changes of colour seem to depend upon some change in the arrangement of the exterior layer of particles of the metal; they cannot depend on oxidation, as they take place under mercury." Stodart convinced him of his error on this point, with the result that the correct explanation was given in later editions, viz.: "These changes of colour seem to depend upon the formation of a plate of oxide, which increases in thickness the higher the temperature."

Wootz and Ancient Indian Steel

It may seem curious to those who have not previously studied this subject that Faraday and other eminent scientists of the early part of the nineteenth century should attach so much importance to the examination of wootz steel. They were, however, justified in doing so, for the manufacture of iron and steel in India goes back, it is quite possible, some thousands of years, and it is evident that wootz, one of the most highly prized products of the Indian craftsmen, was in many respects superior to anything that the steelmakers of Western Europe had hitherto produced. The investigation of its properties and the attempt to imitate them was a very commendable research, but it offered great difficulties under the conditions then prevailing as regards metallurgical knowledge and facilities for scientific observations.

The remarkable progress made in this and other European countries and in America during the latter half of the nineteenth century, both as regards tonnage output and the development of special steels, has resulted in the achievements of Eastern steelmakers being to some extent forgotten. In a monograph on iron and steel work in the Province of Bengal, published in Calcutta, in 1907, by Mr. E. R. Watson, M.A., B.Sc., the author opens with references to the state of knowledge during the period B.C. 1400 to B.C. 150, as gleaned from Vedas, Manu's Code, and the Puranas, supplemented by archæological investigations. The "Vedas" books, written about the fourteenth century B.C., contain several interesting references to iron and steel and weapons, particularly the bow and arrow, swords, spears, javelins, lances, hatchets, and the discus; also numerous references to protective coats of mail. There is also a reference in the *Rig Veda* to the use of razors. In the *Dhanurveda,* which is a subsidiary "Veda," containing only the rules regarding archery, there is a reference to a special arrow, termed the "Náràcha," of which the peculiarity was its construction entirely of iron, whilst of the ordinary arrow only the head or blade was of this metal.

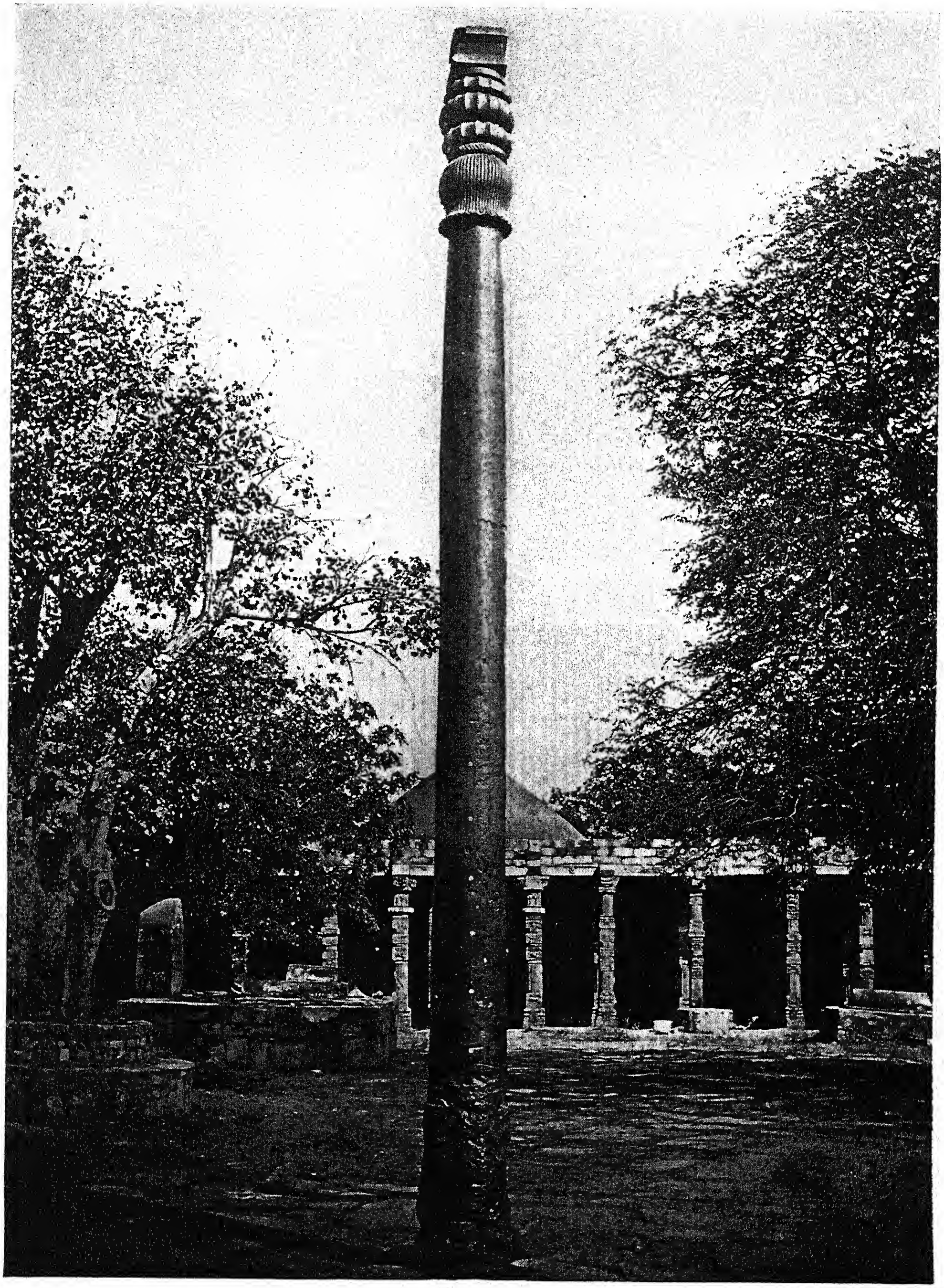
In the *Brhat Sañhitá* of the Varáha Mihria, says Mr. Watson, there is given a most detailed and interesting account of the tempering of swords, which shows that even at this period steel was distinguished from iron, and the nicety of the process of tempering was appreciated, as it was known that very small alterations in the details of the process would materially affect the result. The various recipes given are recommended by statements as to the capabilities of blades which have been subjected to the described

treatments. Thus it is described how to temper a blade so that it will cut off an elephant's trunk, or so that it will be fit for piercing stones, or so that it cannot be whetted on a stone or blunted by other iron instruments. The chief variations in the tempering process seem to have been effected by using a variety of liquids for the quenching—a means which is employed at the present time.

No less remarkable than this early knowledge of the heat treatment of steel are the large dimensions of iron forgings still surviving in some of the ancient temples. For example, large beams of iron were used in building the Black Pagoda of Kanarak. The date of this building is fixed by Fergusson in the latter half of the ninth century, but Stirling gives it a later date, viz., 1241. In front of the entrance to the temple, which is on the east side, amongst the stones, lies a bar of iron, 23 feet long and 11½ inches thick and broad. Iron beams are also employed to support the roof in the Jagamohan or porch, now the only part of the temple standing.

It appears this Black Pagoda possessed a ceiling "with a flat stone roof, supported by wrought iron beams . . . showing a knowledge of the properties and strength of the material that is remarkable in a people who are now so utterly incapable of forging such masses. The employment of these beams here is a mystery. They were not needed for strength, as the building is still firm after they have fallen, and so expensive a false ceiling was not wanted architecturally to roof so plain a chamber. It seems to be only another instance of that profusion of labour which the Hindus loved to lavish on the temple of their gods . . . I do not know on what grounds the beams are described as of *wrought* iron by Fergusson, and I am not aware that any samples of the iron have been taken for chemical analysis or mechanical tests. It may be noted that the celebrated iron pillar at Delhi is supposed to be of about the same age as these beams or even earlier (A.D. 400, according to Fergusson), and that this has been shown to consist of pure wrought iron by chemical analysis." This pillar, which is illustrated in Plate XXIV., has been fully described and analysed by the author as shown in his paper on "Sinhalese Iron and Steel," read before the Iron and Steel Institute, 1912, Vol. I.

These massive pillars in iron, of which those mentioned above form impressive examples, do not appear to have any counterparts in more modern times. Indian smiths continued, however, to practise the manufacture of wootz, using methods which were handed down from father to son, and no doubt varied slightly in different localities and families. This special form of cast steel



The Delhi Iron Pillar.
Dating from the fifth century A.D.

[To face p. 68.

was necessarily made in comparatively small lots as shown on p. 81, and evidently varied considerably in composition, but the finest specimens appear to have been specially good for the manufacture of fine cutting tools and instruments, and wootz was very notable for its damascened surface. It was these properties that aroused the interest of European metallurgists and led to repeated efforts to determine the secret of damascening, and attempts to imitate the qualities of the Indian steel. These efforts were not confined to the Englishmen Pearson, Stodart and Faraday. Similar attempts were made in France by the Société d'Encouragement pour l'Industrie Nationale, who, however, acknowledged that the initiation of alloy steels was by Faraday. None of the European investigators appears to have been specially successful, but with the perfection of Huntsman's crucible steel and the general advance in scientific metallurgy there was no longer any inducement to pursue the problem of imitating wootz.

Interesting and valuable studies on the subject of the damascene process in connection with ancient and modern steel have also been made by the eminent Russian metallurgist, Colonel N. T. Belaiew, C.B., now residing in London. These were described in a course of advanced lectures in Metallurgy delivered by him at the Royal School of Mines, and afterwards published in the form of a book, entitled *Crystallisation of Metals*.

CHAPTER V

SEQUENCE OF EVENTS

Faraday's Interest in "Steel and Alloys"

The intensity of Faraday's interest in his metallurgical researches is shown by the fact that he devoted himself to them for a period of some six years, from 1819 to 1824, with an energy that appears, at times, almost to have exhausted his strength, judging from remarks in certain of his letters. It may reasonably be asked how Faraday, who is best known for his electrical investigations, came to be so deeply interested in steel and its alloys. There are several possible causes, and it is likely that each contributed in some measure to arouse his enthusiasm.

In the first place, Faraday was the son of a smith and he said in later years: "I love a smith's shop and anything relating to smithery." Also he regarded himself principally as a chemist during his earlier years at the Royal Institution. What more natural than that a research involving chemical investigation of steel should have appealed to him?

Again, one of the famous four lectures in 1812 by Sir Humphry Davy on "Chemical Philosophy," the "reporting" of which won Faraday—then twenty-one years of age—his first appointment at the Royal Institution, dealt with Metals; this, no doubt, had some effect in stimulating his interest in the subject. Professor Brande, who succeeded Davy as Professor of Chemistry at the Royal Institution, and under whom Faraday worked for a number of years, was also interested in metals and metalliferous productions, as witness his *Manual of Chemistry*, first published in 1819. He doubtless encouraged Faraday in his researches on alloys.

The managers of the Royal Institution had passed a resolution in the year 1802 to the effect that experiments should be carried out on alloys of metals. This was, of course, a much broader and a vaguer project than the scheme of research which Faraday undertook as regards the alloys of steel. Nevertheless, it is most probable that he was aware of the managers' minute which may thus be credited with endorsing, if not actually contributing to, the inspiration of his research.

PROFESSOR ARTHUR AUGUSTE DE LA RIVE, F.R.S.
1801–1873.
Bust unveiled in the Peristyle of the University, Geneva, September 8th, 1902.

[*To face p.* 70.

While mentioning all these possibilities, the author is inclined to regard them rather as contributory or predisposing factors. In the author's opinion, the two main reasons for Faraday's embarking on the difficult work of metallurgical research were: (i) the great amount of interest aroused by wootz about that time; and (ii) Faraday's innate genius and foresight which led him to appreciate the fact that steel could be improved by suitable alloying and that such improvement was well worth seeking.

Faraday would be brought closely into touch with the problem of wootz by his association with James Stodart, who had already been engaged on the examination of this material in collaboration with Dr. George Pearson, and was so far convinced of its merits that his trade cards of about 1820 said that he preferred wootz to ordinary steel after many years of comparative trial. From this and other evidence it is clear that Stodart was thoroughly familiar with wootz from the practical standpoint for some years at least before he and Faraday collaborated in the steel researches. In his obituary notice of Faraday, published in the *Bibliothèque Universelle et Revue Suisse,* Vol. 30, October 15th, 1867, Professor A. A. de la Rive, who was a great friend of Faraday, states definitely that it was by the analysis of the Indian steel called wootz that Faraday was led, in collaboration with Stodart, to make certain iron alloys which had all the properties of this steel—that is, by combining " alumina " with the iron and carbon.

Admitting this, it must still be remembered that Faraday's investigations of steel and alloys ultimately went far beyond the mere imitation of wootz. Doubtless he was led on to these further investigations by his own prescience and genius for research, which led him to enquire—by experiment and manipulation—whether it was not possible to improve the cheap and abundant metal iron by alloying it with other elements. The wonderful effect of carbon in changing iron to steel was sufficient indication that further improvements might be possible by other additions. In supposing this, Faraday was in every way correct. There was a great future in store for alloy steels, but many difficulties had to be overcome, and much more was necessary in the way of general metallurgical knowledge and facilities than was available in Faraday's time, before full success could be achieved. Nevertheless, research in the field of alloy steels may justly be said to have commenced with Faraday's work and, as will be shown later, he attained a considerable measure of success, as judged by the standards and under the conditions of his day.

General Sequence of Events

At this point it will be helpful to give a summarised statement of the sequence of events with which we are specially concerned in this book. These commenced near the end of the eighteenth century, when Dr. Helenus Scott, of Bombay, sent samples of wootz steel to Sir Joseph Banks, P.R.S. The samples in question were investigated by Dr. George Pearson, F.R.S., and others, among whom we find Mr. James Stodart, F.R.S., the cutler and maker of surgeon's instruments. Stodart, as a member of the Royal Institution, came into touch with Michael Faraday, at that time assistant to Sir Humphry Davy, P.R.S., in the laboratory of the Royal Institution. In 1819 Faraday undertook an analysis of part of one of the cakes of wootz that had been presented to Stodart, the two men having already embarked upon their investigation of alloys of steel with some sixteen different elements, besides four special compounds. This work proceeded most actively during the period 1819–1822. From the whole tone and substance of Stodart and Faraday's paper presented to the Royal Society in 1822, it is probable that the work was continued with undiminished hopes until Stodart's death in 1823. After that, with the exception of the notes in Faraday's Diary referred to on p. 125, no record or trace is to be found of any later work. Faraday's last experiment on the metallurgy of steel alloys appears to have been performed in June, 1824, and thereafter in all his many writings there is scarcely any reference to metallurgy,* and none in any way following up his work of 1819–1824 on the alloys of steel.

Such, briefly, is the tale of a gallant adventure conducted half a century or so before its time by a handful of men aided by little save their intuitive faith and a praiseworthy perseverance. Other characters cross the stage, all of them belonging to the Royal Society—among them Mr. W. H. Pepys, who failed to recognise the superiority of wootz, Dr. Thomas Thomson, who co-operated with Sir Humphry Davy in experiments on temper colours, Dr. J. G. Children, who assisted Faraday in the matter of analyses, Professor W. T. Brande, the well-known chemist, and Dr. W. H. Wollaston, whose generosity provided large quantities of rare elements for the preparation of alloys —but, above all these, is Faraday himself, probably the sole

* In 1836, Faraday wrote a paper "On the General Magnetic Relations and Characters of Metals" (*Phil. Mag.*, Vol. VIII.); in 1845, one "On the Magnetic Relations and Characters of the Metals" (*Phil. Mag.*, Vol. XXVII.); and, in 1858, one "On Platinum" (*R. I. Proc.*, Vol. III.). In 1863, when he was seventy-two years of age, Faraday could not even remember what had happened to his husbanded specimens of alloy steels (see p. 126).

instigator as he was certainly the most laborious worker in the first deliberate attack upon the rich but difficult field of alloy steels. As regards the industrial or practical utilisation which was made of Faraday's work, little can be said except that it commenced with fair promises but suffered an early death. Some, at least, of Faraday's alloys were made "in the large way" at Sanderson's works in Sheffield, and it appears that fenders were made of his silver-alloy steel by the firm of Green, Pickslay & Co., in Sheffield. Apparently, a certain number of razors were made for sale, using rhodium, iridium and silver alloys of steel, but no clear evidence can be obtained of the extent of these and any other practical uses to which Faraday's alloys may have been applied, and the most diligent search has revealed no trace of any surviving specimens of these products. Some interesting letters from Green, Pickslay & Co. to Faraday are given in Chapter VI.

It may be added that, judging from some of the business literature of that day, it also seems probable that certain makers of crucible steel made use of the expressions "Wootz Steel" and "Silver Steel" as merely trade terms under which they offered their products to the public.

Stages of Faraday's Work on "Steel and Alloys"

The whole history of Michael Faraday's career shows that he had only to be brought into contact with any scientific problem in order to become interested in its solution. So great was his genius, so broad his outlook, and so marked his powers of observation and deduction that, in every case, he added greatly to human knowledge of the problems to which he addressed himself. In order, therefore, to explain how Faraday came to embark on his researches concerning steel alloys, it is only necessary to show how he came into contact with the subject, and that has been done in the preceding pages. Once the opportunity was afforded to him, he worked zealously at the problems which he set himself until circumstances compelled him to desist. But for the untimely death of James Stodart, which robbed Faraday of his collaborator on the practical and commercial side at a crucial stage in the research, the investigation would almost certainly have been carried on. There is no note of pessimism or disappointment in the Royal Society paper of 1822. On the contrary, very promising results had been obtained, and there appear to have been good prospects of industrial developments. Faraday, however, was tied to the Royal Institution building, and had increasing duties and responsibilities there. He could not go to Sheffield to conduct

or supervise large-scale production, and the death of Stodart at this stage must have been a determining factor in causing Faraday to set aside his steel researches. The pressure of other affairs, and the long series of electrical investigations on which he embarked soon afterwards, prevented him from ever returning to the metallurgical field.

Faraday's active association with research on steel and alloys thus commenced about the year 1819 and ended about the year 1824, a period of only six years, though he was doubtless interested in the subject in a general way for a much longer period, as witness the fact that he occasionally presented to friends, in later years, razors made from his own special steel. The analysis of one of these razors is given on p. 240. Though he asked his friend Professor G. de la Rive to pity him that he had got no further after so much labour, the wonder is that he was able to accomplish so much in this difficult field with the few and, as judged by modern standards, hopelessly inadequate resources then available. Those of a later day do not always find it easy to appreciate the many difficulties and assess the services of the pioneer.

Faraday's association with steel may conveniently be considered as coming under five headings. First, there was his examination of wootz or Indian steel as set forth in his paper, "An Analysis of Wootz, or Indian Steel," read before the Royal Institution in 1819.

Second, there was the series of experiments, jointly with Stodart, described in the paper, "Experiments on the Alloys of Steel made with a View to Its Improvement," presented to the Royal Institution in 1820. In the course of these experiments Faraday was able to imitate the beautifully damascened surface shown by wootz steel when etched with acid, by means of a steel alloyed with "the metal of alumine"—that is, aluminium. Having once embarked on the investigation of steel alloys, Faraday appears to have mapped out a complete programme with his customary thoroughness and brilliant genius of conception. An account of his laboratory experiments at the Royal Institution is given on pp. 111 to 116 of this book. These experiments were so successful that they led to the third phase, viz., a further two years of investigations in the laboratories of the Royal Institution, culminating in the fourth stage—that of large-scale production at Sheffield—as noted below.

The third stage and, to some extent, the fourth stage are represented by Stodart and Faraday's paper, "On the Alloys of Steel," presented to the Royal Society in 1822. Both the second and third sets of experiments were undoubtedly conducted by Faraday at the Royal Institution, and, as far as the author is able to judge, these

experiments are probably represented by the seventy-nine specimens which have survived to the present day and have now been examined at the Hadfield Research Laboratories. The preparation, investigation and description of the specimens in the Royal Institution and Royal Society papers were undoubtedly the work of Faraday, and were definitely carried out at the Royal Institution in Albemarle Street. No doubt he received a considerable amount of assistance and advice from Stodart in regard to the testing of the working qualities of the steels and the manufacture of sample tools and instruments, but the scientific as apart from the steel user's side of the work was almost certainly that of Faraday alone, and the same may be said of the preparation of the papers. Anyone who has studied these papers, and also Faraday's wonderful book on *Chemical Manipulation*, can come to no other conclusion.

The fourth stage or section of Faraday's connection with steel is represented by experiments on a larger scale carried out at Sheffield by Faraday's representative sent down there to Messrs. Sanderson's works.

It appears from the letters quoted on p. 133 that at a later date between 1824 and 1826 alloys of steel and silver were being used by Messrs. Green, Pickslay & Co., of Sheffield, for various descriptions of cutlery as well as for the fronts of stoves and fenders. The same firm was also experimenting with alloys of steel and rhodium, iridium and silver, of which they sent specimens to Faraday. This work, the practical application on a manufacturing scale of Faraday's discoveries, may be regarded as the fifth stage of his association with steel alloys. These alloy steels were prepared at the works of Green, Pickslay & Co., their manufacture and use being derived from Faraday's instructions, and were thus the direct outcome of his conception.

Unfortunately, no records have been found in Sheffield bearing on these matters, though a thorough search has been made. Messrs. Sanderson's name still continues in the firm of Messrs. Sanderson Bros. and Newbould, Ltd. The firm of Green, Pickslay & Co. has died out, but some interesting information regarding this concern is given in Chapter VI.

Not a trace of the experimental ingots made for Faraday in Sheffield can be found, but there is no doubt that they were on quite a large scale compared with the tiny buttons and bars made at the Royal Institution. With the facilities there available, Faraday could only deal with small quantities of steel, and his largest specimens do not appear to have exceeded about 1 lb. in weight, if, indeed, they were as large as that. The total weight of

the seventy-nine specimens entrusted to the author for examination only slightly exceeds 7¾ lb. (7 lb. 14 oz., to be exact). On the other hand, the experimental ingots made in Sheffield reached 10 to 20 lb. each, and it is probable that the ingots used by Green, Pickslay & Co. for their fenders and other purposes were of a yet larger size.

Stodart's Share in the Work

From what has already been said concerning James Stodart in this chapter, and in Chapter III., *Dramatis Personæ,* it will be realised that his share in Faraday's research on alloy steels was almost certainly restricted to practical advice and assistance in regard to the working and applications of specimens, the manufacture of trial cutting instruments and the like and, in fact, to providing a link between Faraday in his laboratory and the world of steel users. As shown on p. 40, at one stage in his career Stodart published several communications on scientific subjects. He was undoubtedly a man of very considerable ability, but for many years prior to his association with Faraday he had published nothing in the way of papers, and it is quite fair to assume that the papers of 1820 and 1822 on steel and alloys would never have appeared but for Faraday. They may, in fact, be regarded as entirely Faraday's work except that Stodart doubtless assisted in the manner described above, in the "applied" side of the research.

An interesting proof of Stodart's long association with the problem of damask steel, as well as an instance of his practical skill and scientific bent, is to be found in a letter to Mr. William Nicholson, of the *Journal of Natural Philosophy, Chemistry and the Arts*, published in Vol. VII. of that publication in 1804, giving an account of an experiment to imitate Damascus sword blades. The letter reads as follows :—

"To Mr. Nicholson

"Dear Sir,—Having lately had an opportunity of examining some sword blades, which appeared to be defective, I was induced to make the following experiment.

"The subject is surely of some importance, and perhaps never more so than at the present moment.

"We hear of swords having broken in battle, and we can hardly imagine a more distressing circumstance.

"Those which I have seen are certainly in no danger of failing in that way, for on the contrary they are evidently too soft, and consequently cannot form a good cutting edge.

"I am not acquainted with the process used in making sword blades,

but am inclined to suspect that the price allowed is not equal to the labour necessary to form a good instrument.

" The following method, which I believe to be nearly the same as that practised at Damascus, but which I suspect would be too difficult and expensive for general application, may perhaps lead to some more simple method of accomplishing the desired purpose.

" I took six small bars of good malleable iron, and the same number of sheer steel, and laid them one on another alternatively, as if forming a galvanic pile ; I then with the assistance of an expert workman, committed them to a clean forge fire, and with care we succeeded in welding them into a solid lump.

" This was forged into a stout flat plate, which being heated to whiteness, was by means of strong tongs twisted spirally until it formed a cylindrical tube.

" In this twisted state it was heated, hammered flat, and again welded, and after being forged into a convenient form and substance, was doubled through its whole length, somewhat in the manner of the back of a saw.

" A slip of good steel was inserted, and another welding heat taken, which consolidated the whole mass.

" I need not say this slip of steel was intended for our edge.

" The remaining part of the process was simple ; it consisted only in forging it into the shape of the blade we wanted ; which on examination proved perfectly sound in every part.

" Being eager to witness some proofs of excellence and beauty which my expectation had anticipated, I too hastily and without due consideration proceeded to harden it by heating and quenching in water ; and had the misfortune to see it cracking in seven or eight different places.

" I have no doubt this was occasioned by the unequal expansion and subsequent contraction of the different parts of the mass.

" In my next trial I shall guard against this accident.

" Enough however remained sound to prove it both good and beautiful ; the edge bears the severest trials at the same time that the whole blade has sufficient tenacity.

" I have polished a part of it, and by applying a weak acid, produced an appearance, which though by no means equal to the beauty of what is called the Damascus water, leaves me little reason to doubt of accomplishing that appearance in my next trial.

" My intention is to multiply my pieces of metal, to repeat the process of twisting, and certainly not again to quench in water.

" I shall take the liberty to transmit to you an exact account of my next experiment, and if successful, to accompany it with a sample of the metal formed into a blade of some kind or another.

" I am with much respect,
Dear Sir,
" Your obedient Servant,

" Strand, Jan. 19th, 1804. " J. Stodart.

" P.S.—Why is the appearance produced on Damascus steel by the application of an acid called the water ? [sic].

"Is it not the different degrees of oxidation? * and what is the acid best fitted to produce this appearance.

"I had a paper given me some ten years ago on this subject, by a gentleman whose name I do not know. Unfortunately I have mislaid it.

"In addition to what you have published on the subject in your valuable Journal, pray furnish us with any other facts that may have come to your knowledge since that period.

"The subject appears to me to be worthy of philosophical research, and perhaps of national encouragement.

* "I have always supposed steel to be less readily soluble than pure iron; and that the carbon which is seen on the face of the former during the process of damasking defends it from the acid, while the fibres of iron are etched by corrosion so as to exhibit the peculiar waving lines of this operation.—N."

It is interesting to note from this letter that Stodart, who, as pointed out on p. 42, had the distinction of convincing Sir Humphry Davy that oxidation was the cause of temper colours, was himself in error when he attributed the damask of steel to a similar cause. Mr. Nicholson, as shown by his footnote, had a clearer understanding of the action.

Direct evidence of the practical assistance which Stodart gave Faraday in the research on steel and alloys is to be found in the fact that one of the seventy-nine specimens in Faraday's box is a portion of a knife blade bearing the name STODART.

NATIVE AND NATURAL ALLOYS

From what has been already said, it will be realised that the native Indian steel or wootz, which Faraday stated that he found to be an alloy of steel with "alumine," formed one of the starting points in his great research. Another was provided by meteoric iron which was reputed to have somewhat remarkable properties. Before proceeding to a full description of Faraday's facilities, procedure and results, it will be useful to give further particulars of his work on wootz, together with other contemporary and later information. In addition, some interesting notes on meteoric iron will be presented, and the reasons which led Faraday to go from base to noble alloying elements will be considered.

WOOTZ

This material, the name of which is of doubtful etymology, is defined in *Ogilvie's Dictionary* (1884) as :—

"A very superior kind of steel made in the East Indies, it is believed, by a process direct from the ore, and imported into Europe and America for making the finest classes of edge tools.

"Faraday attributed its excellence to the presence of a small quantity of aluminium, but more recent analyses of samples have been made in which aluminium has not been discovered."

According to the *New Oxford English Dictionary*, the word *wootz*, sometimes spelt *wudz*, is believed to have originated in a misprint for *wook*, representing the Kanarese *ukku* (pronounced with an initial *w*). The meaning given for the word is "a crucible steel made in Southern India by fusing magnetic iron ore with carbonaceous matter." The author is indebted to Sir John Marshall, C.I.E., Director-General of Archæology in India, for further information, as follows:

"Wootz steel is said to be made specially by the aborigines of Southern India, like the Kotas of the Nilgiris. The Kanarese *ukku* is a later form of *urku*. *Ukku* is also a Telugu name of steel. Consequently it is not quite correct to say that wootz is derived from the Kanarese *ukku*. Nor is it known whether the word wootz correctly represents the original Dravidian name for steel. In Tamil as well as in Malayālam *urukku* is the name of steel. The different forms mentioned above—*urku* or *ukku* in Kanarese, *ukku* in Telugu and *urukku* in Tamil and Malayālam—would point to a common Dravidian origin of the term, whatever that may have been. There is no word for steel in the Indo-European languages, as far as I am aware, which would phonetically correspond to wootz.

"The Tamil *urukku* is derived from the root *uruku*, meaning 'to fuse,' etc. This Tamil root, though written as *uruku*, is pronounced as *uruhu*, there being no symbol for *ha* in Tamil. The Tamil pronunciation of this letter *ka* is a mixture of guttural, aspirate and sibilant sound."

In the *Encyclopædia Britannica*, Supplement III., 1824, just after Faraday's experiments were carried out, a reference is made, and it is stated that "Wootz, a steel from India, has lately been successfully employed for cutlery."

A material of such reputation was naturally of special interest in the earlier part of the nineteenth century, and its interest for us to-day is greatly increased by the fact that wootz appears to have been largely responsible for Faraday's embarking on his researches concerning alloys of steel.

Late in the eighteenth century, Dr. Helenus Scott, of Bombay, sent specimens of wootz steel to Sir Joseph Banks, then President of the Royal Society. The nature and properties of this material were investigated by Dr. George Pearson, F.R.S., whose results were presented to the Royal Society in due course, and published in the *Philosophical Transactions* for 1795.* At the instance of Sir Joseph Banks, various professional and other persons assisted Dr. Pearson in this enquiry, and among them was "that ingenious

* "Experiments and Observations to Investigate the Nature of a Kind of Steel Manufactured at Bombay, and there called Wootz: with Remarks on the Properties and Composition of the Different States of Iron," by George Pearson, M.D., F.R.S., read June 11th, 1795.

artist, Mr. Stodart," who, says Dr. Pearson in his paper, "forged a piece of wootz at the desire of the President, for a pen-knife, at the temperature of ignition in the dark. It received the requisite temper ("at the temperature of 450° Fahrenheit's scale," Dr. Pearson adds, in a note from Mr. Stodart's letter to Sir Joseph). The edge was as fine and cut as well as the best steel knife. Notwithstanding the difficulty of labour in forging, Mr. Stodart from this trial was of opinion that wootz is superior for many purposes to any steel used in this country. We thought it would carry a finer, stronger and more durable edge and point. Hence it might be particularly valuable for lancets and other chirurgical instruments."

It was found that this wootz could only be forged at a low red heat, and even then not without much care; at a higher temperature it cracks or crumbles to pieces under the hammer. It is capable of acquiring great hardness. It was stated by Dr. Scott, of Bombay, who provided the specimens examined by Dr. Pearson, that wootz cannot be welded either with iron or steel.

Notwithstanding the uncertainties surrounding the nature and manufacture of wootz, and the difficulty of manipulating this particular variety of steel, it appears that Mr. Stodart was very successful in applying it to the manufacture of surgical instruments, razors and other articles in which great perfection and durability of edge was required. Among other applications, he used it to make the knife edges for Captain Katers' original invariable pendulum.

In their famous *Practical Treatise on Metallurgy*, Vol. III., published in 1870, Sir William Crookes, F.R.S., and Dr. Ernst Rohrig, Ph.D., M.E., describe the production of Indian steel or wootz (natural damask) in considerable detail. After explaining the method of supplying the ore and fuel to the furnace they say :—

> "The bellows are worked for three or four hours, when the process is stopped; the temporary wall in front being broken down, the bloom of more or less carbonised iron, about 40 lb. in weight, is removed by a pair of tongs from the bottom of the furnace.
>
> "It is then beaten with a wooden mallet to separate from it as much of the scoria as possible, and while still red hot, it is cut through the middle, but not separated, the incision being merely to show the quality of the interior of the mass.
>
> "In this state it is sold to the blacksmith, who makes it into bar-iron.
>
> "The proportion of such iron made by the natives from 100 parts of ore is about 15 parts, or about 12 per cent. of very pure wrought-iron."

At the Royal School of Mines, South Kensington, there is a most interesting exhibit of specimens of wootz steel, provided by Sir Thomas Holland, K.C.S.I., K.C.I.E., F.R.S. The various exhibits

show the successive stages in the production of wootz steel, including (*a*) the raw materials—that is, the ore, the wood, and type of charcoal employed ; (*b*) small crucibles, 5 or 6 inches in height and about $2\frac{1}{2}$ inches in diameter, with their contents, iron and wood, all ready for putting into the furnace used for melting, worked by bellows ; (*c*) the used crucibles ; (*d*) crucibles containing the fused metal ; and, finally, (*e*) the " cakes " of wootz.

In the description accompanying these exhibits it is stated that " . . . 14 to 24 crucibles at a time were heated in the pit for 3 to 4 hours, the fire being urged by a bellows . . . The steel thus obtained, which contained a high percentage of carbon, was used for tools and knives."

Analyses of wootz steel conducted by the chemist Mr. T. H. Henry gave the following results : Carbon combined, 1·333 ; carbon uncombined, 0·312 ; silicon, 0·045 ; sulphur, 0·181 ; arsenic, 0·037 ; iron, by difference, 98·092 per cent. The specific gravity of this wootz was 7·727 at 62° F., a value which may be compared with the following observations published by Dr. Pearson :—

	Sp. Gr.
Wootz	7·181
Another specimen of wootz . . .	7·403
The same, forged	7·647
Another specimen, forged	7·503
Wootz which had been melted . . .	7·200
Wootz which had been quenched while white hot	7·166

It is evident that Pearson's work, excellent though it was for that early date, by no means cleared up the mystery of wootz, for more than twenty years later, that is, in 1819, we find Faraday engaged upon the same problem. The following paper, reproduced from the *Quarterly Journal of Literature, Science and the Arts,** is interesting not only as regards the information which it presents on the subject of wootz, but also from the light it throws on Faraday's reasons for undertaking this research. It also bears witness to the extraordinarily careful and methodical manner in which he worked :—

" *Art. VIII. An Analysis of Wootz, or Indian Steel.* By M. Faraday, Chemical Assistant to the Royal Institution.

" The object of the following experiments being to ascertain whether any other substances were present in the wootz than iron and carbon, no attention was given to the relative proportions of these two bodies.

* Vol. VII. Royal Institution of Great Britain, April 24th, 1819, pp. 288, 290 (London : John Murray, Albemarle Street).

"The process was therefore much simpler than would otherwise have been required, and was conducted in the following manner:—

"A piece of wootz, weighing 164·3 grains, was placed in a flask, and acted on by nitro-muriatic acid and heat.

"It gradually dissolved, and dark-coloured flakes separated from it, which were unalterable in the acid, though boiled with it.

"When all action had ceased, the solution was poured off from the sediment (*a*) which was repeatedly washed with distilled water; the solution was then examined carefully, but I could find nothing in it but iron.

"Whilst washing the sediment (*a*) it separated into two parts; a black powder (*b*) sank to the bottom of the water poured upon it, whilst a reddish brown substance (*c*) in flocculi remained suspended; these were parted from each other.

"The black powder (*b*) was fused with potash in a silver capsule, and then dissolved in water; it deposited a brown powder (*d*), and a clear alkaline solution was obtained.

"This was saturated with muriatic acid, and evaporated to dryness, and then being redissolved with a little excess of muriatic acid, a very small quantity of white flocculi were left untouched, which were insoluble in acids, and had the characters of silex.*

"The solution acted on by subcarbonate of potash gave an abundant precipitate.

"This was washed, and when heated with a little solution of potash, dissolved in it like alumine.† Sulphuric acid was then added, and a solution of alum was obtained, a small quantity of silex precipitating.

"The brown powder (*d*) deposited by the alkaline solution, was treated with nitric acid; a little heat being applied, nearly the whole was dissolved immediately, leaving a little of a black substance.

"The filtered solution gave a precipitate with muriate of soda, but when ammonia was added to it, the precipitate was redissolved, and a small quantity of iron was thrown down.

"The solution contained, therefore, silver, from the capsule in which the fusion had been made, and iron derived from the wootz.

"The black substance left by the nitric acid, was nearly all dissolved by nitro-muriatic acid, iron being taken into solution, and a little of the substance (*b*) remaining.

"The reddish-brown substance (*c*) was not affected by nitric acid, but, on adding solution of pure potash to it, a clear deep brown solution was obtained, and a blackish brown sediment (*e*) remained.

"When the alkali of the solution was neutralized by muriatic acid flocculi were precipitated, and the solution became colourless.

"These flocculi, collected together and dried, proved to be combustible, and appeared to be merely modified tannin.

"The brown sediment (*e*) being then examined by muriatic acid, gave oxide of iron and a little silex.

"I have detailed the process of analysis at length, because from the small quantities of silex and alumine obtained, doubts otherwise might have arisen respecting their sources.

* *Silex* = a word formerly used to designate any flinty substance, also as an equivalent of silica.

† *Alumine* = alumina.

"The wootz, operated upon the above experiment, was part of one of the cakes presented by the Right Hon. Sir Joseph Banks to Mr. Stodart.

"The piece was cut from the middle of the cake when heated to a cherry-red colour; consequently, it was submitted to chemical analysis in the same state in which it came from the crucible of the Indian steel-maker.

"In some other experiments 460 grains gave 0·3 of a grain of silex, and 0·6 of a grain of alumine.

"Mr. Stodart at the same time furnished me with another specimen of Indian steel, expressing a wish that it also might be submitted to analysis.

"This, too, was in the same state in which it was imported.

"The appearance of it, whilst being acted upon by acid, was very different to that of the wootz, and 625 grains gave me no silex, and only fifteen-hundredths of a grain of alumine.

"420 grains of the best English steel furnished by Mr. Stodart were acted on, but I could obtain no earths from it.

"A slight appearance of opacity in a solution was at last produced, which I ascertained to be alumine contained in the tests I had used.

"Many comparative experiments were afterwards made with the three specimens of steel, those from India always appeared perfectly distinct from each other in the kind and quantity of earths they gave, and the English steel invariably appeared without the earths; neither was the slightest reason offered for the supposition I at first entertained, that the earths came from the tests used in the analysis.

"Being engaged in the laboratory of the Royal Institution with Mr. Stodart, in a series of experiments on the alloys of steel, I was desirous among other researches to make an experiment, with a view to imitating wootz."

(This is an important paragraph because it is the first reference, on April 24th, 1819, to the researches being carried out on alloys of steel.)

"In this, however, I have not yet been very successful; I have obtained specimens of iron, giving abundance of silex and alumine on analysis, and such alloys or combinations have been obtained by others; but they never present the appearance of wootz during the action of acids upon them, even though the metal used in making the alloy be in the state of steel; and if wootz owes its excellence to any portion of the bases of the earths, silex or alumine, combined with it, those substances must, I think, be either in a more perfect or in a different state of combination to what they are in alloys obtained by fusing for three or four hours in contact with wood and the earths."

It will be seen from the above that Faraday states definitely that the object of the analysis was to ascertain *whether wootz contained any other substances than iron and carbon.* He also refers to the fact that he was at this time (April, 1819) engaged in the laboratory of the Royal Institution with Mr. Stodart *in a series of experiments*

on the alloys of steel, and was *desirous among other researches . . . of imitating wootz.* It is very clear that Faraday was imbued with the idea of a systematic investigation of steel alloys and that he would never have consented to spend so much time and labour on this research if he had not believed in the possibility of obtaining valuable new materials by this means. It was left for later workers to show the full extent of those possibilities, and even to-day, with our vastly greater resources, we have not finished exploring the field which Faraday opened.

In a remarkable book published in 1846, entitled *Mémoire sur la Fabrication et la Commerce des Fer à Acier dans le Nord de l'Europe*, the author, M. F. le Play, Ingénieur en chef des Mines, Professor de Metallurgie à l'École Royale des Mines, mentions that Faraday and Stodart's experiments in 1820 commenced owing to Faraday's having analysed certain specimens of material from India, known as wootz steel, but it would certainly seem from Faraday's paper to the Royal Institution in 1819 (reproduced above) that he was engaged on the investigation of alloys of steel before he analysed wootz and that he analysed wootz with a view to imitate this material by an alloy. However this may be, a similar series of experiments on alloys of iron was then undertaken in France with the assistance of the well-known Société d'Encouragement pour l'Industrie Nationale, a society still existing and doing most excellent work. This society found the necessary funds for carrying out some three hundred experiments upon alloys of iron with different metals. A report on this subject was presented to the society in 1821. The experiments were continued to the year 1824, but did not appear to result in any commercial development. The Société d'Encouragement pour l'Industrie Nationale then awarded gold medals to several investigators in the art of steel-making.

Though the French investigations were no more successful than Faraday's in regard to any immediate practical application, notwithstanding the liberal support of the Société and the labours of "several investigators," it is clear that the scientific institution in question, by awarding gold medals, realised the importance of the work that had been done. Hitherto, we in this country have done less than justice to Faraday for his labours in this direction, but at any rate it was admitted in France that he was the pioneer in alloys research.

The subject of wootz steel evidently continued to exercise the minds of English steelmakers for many years. Thus, in the *Edinburgh Phil. Journal*, Vol. IX., April-October, 1823, there

appears an excerpt from the *Ceylon Government Gazette* concerning a report presented by Mr. Russell to the Literary and Agricultural Society of Ceylon on the subject of smelting the iron of that country. "The extraordinary and valuable quality possessed by this metal, in being malleable immediately from the furnace, will probably attract attention among our manufacturers at home, to whom such a property must in many instances prove inestimable." No doubt this was a kind of wootz.

Then again, in his book, *On the Assaying of Iron Ores*, David Mushet devotes a considerable amount of space to the subject of wootz ore. The following information is specially interesting :—

"In 1826, Heath brought home from India 20 tons of wootz ore for the production of steel in the most advantageous manner. The richness of the ore, as previously ascertained, varied from 70 to 72 per cent. As there was no hot blast at that time and the ore was nearly without earthy matter, considerable anxiety was felt as to the correct line to pursue. After bringing the ore from India, it was important that no error should take place which might prove fatal to the establishment of the fact that iron for steel could be supplied other than from Sweden and Russia.

"After most careful examination, experiment and calculation, the artificial matrix chosen was limestone from the Forest of Dean and a fusible argillaceous schist. The Tintern Abbey furnace was obtained and being in good condition at the time mainly contributed to the success of the experiment. The first burden consisted of :

Wootz ore	51
Limestone	26
Shale	23
	100

The first furnace charge, 3½ cwts. to 4 baskets of charcoal, was composed as follows :

Wootz ore	199·92
Limestone	101·92
Shale	98·16

The new charge was filled on the old, but turned out to be more fusible than the old, and overtook it before reaching the hearth, producing black cinder, white iron, and injuring the tuyere. The second cast was grey mottled, and was probably the first cast iron ever derived from wootz ore. The third charge and several others were smooth-faced foundry iron. The total iron produced was 12 tons 9 cwts,

	Tons.	cwts.
No. 1	6	0
Bright	2	0
Mottled	2	0
White and scraps	2	9

in all, upwards of 62 per cent. from the ore. This pig iron was afterwards converted in various ways into steel-iron and steel, the reception of which in the Sheffield market was so satisfactory as to determine Mr. Heath to erect furnaces in India, where a considerable quantity of pig iron, of an excellent quality, has since been made, and is now making and being brought home to this country to be manufactured into steel-iron.

"In India Mr. Heath possessed immense advantage in the rapid growth of cord wood, and in the superior weight and quality of charcoal it afforded."

Further experiments described by Mushet relate to the fusion and reduction of wootz ore in a crucible. The ore fused alone produced a material somewhat resembling hematite. When heated with charcoal, the ore yielded from 63 to 68 per cent. of metal in the form of malleable iron or crude steel, according to the proportion of charcoal used. Other tests of wootz ore with a siliceous matrix gave results from about 35 to 40 per cent.

Much more might be said concerning this interesting material but the particulars given, specially from the first quarter of the nineteenth century, show how highly wootz was esteemed at that time, what a tantalising problem it offered to the investigators of those days, and how it was closely associated with if not actually responsible for Faraday's long and patient labours in the difficult field of steel alloys. He visualised possibilities which he could not fully realise, but such has been the fate of almost every pioneer. The wonder is that, with the knowledge and facilities then available, he did so much.

Meteoric Iron

A good deal of interest appears to have been attracted by meteoric iron about the time that Faraday commenced his researches on alloy steels, and the material was, no doubt, of special interest to Faraday from the fact that it was reputed to be non-rusting in nature.

The following extract from the *Journal of Science and the Arts*, Vol. VI., 1819, is instructive :—

"*Meteoric Iron in North America*

"The northern Esquimaux visited by Captain Ross, were observed to employ a variety of implements of iron, and upon inquiry being made concerning its source by Captain Sabine, he ascertained that it was procured from the mountains about 30 miles from the coast. The natives described the existence of two large masses containing it. The one was represented as nearly pure iron, and they had been unable to do more than detach small fragments of it. The other, they said, was

a stone, of which they could break fragments, which contained small globules of iron, and which they hammered out between two stones, and thus formed them into flat pieces, about the size of half a sixpence, and which let into a bone handle, side by side, form the edges of their knives. It immediately occurred to Captain Sabine that this might be meteoric iron, but the subject was not further attended to till specimens of the knives reached Sir Joseph Banks, by whose desire Mr. Brande examined the iron, and found in it more than three per cent. of nickel. This, with the uncommon appearance of the metal, which was perfectly free from rust, and had the peculiar silvery whiteness of meteoric iron, puts the source of the specimens alluded to out of all doubt. The one mass is probably entirely iron, and too hard and intractable for their management; the other appears to be a *meteoric stone*, containing pieces of iron, which they succeeded in removing, and extending upon a stone anvil.

" Some experiments upon the power of an alloy of iron with nickel to resist rust, and upon its fitness for delicate cutting instruments, are now in progress, with the results of which we shall in due time acquaint our readers."

Faraday conducted experiments on such alloys at an early stage in his research and, as noted in Chapter VI., he concluded that nickel alloyed with iron had some effect in preventing oxidation, though certainly not to the extent that had been attributed to it, while, on the other hand, nickel alloyed with steel appeared to accelerate the rusting.

Faraday's Use of Noble Metals

It may at first seem curious that Faraday should have experimented with the use of such rare metals as platinum, iridium, rhodium, osmium and palladium in the alloying of steel. Possibly he may have been influenced by the thought that the most likely way of improving the qualities of steel would be to add " noble " metals such as gold, refractory metals such as platinum, and so on. In the absence of any existing knowledge on the subject, such a thought would have been quite reasonable. Also, as suggested by a phrase in the report on French experiments undertaken to confirm and continue Faraday's work to which reference is made on p. 256, " it is a natural idea to harden steel as one hardens copper."

Another fact which should be remembered is that the elements now used so extensively in alloy steels—manganese, nickel, silicon, aluminium, chromium, tungsten, cobalt and others—were then (1819–1824) very difficult to obtain. Singular to say, platinum, though expensive, was much cheaper at that time than now. Faraday had the advantage of obtaining generous supplies of this and its associated metals from Dr. Wollaston, whose assistance he

acknowledged on several occasions. It is definitely stated in one of the Stodart and Faraday papers that the use of rhodium was suggested by Dr. Wollaston, who first discovered this element in crude platinum ore in the year 1803.

In view of the attention devoted by Faraday to the production of alloys of iron containing platinum and rhodium, and bearing in mind that he hoped to find such alloys specially suitable for mirrors, it is interesting to find, in a recent article dealing with the new extension of the Acton Precious Metals Refinery of the Mond Nickel Company, Ltd., a number of references curiously reminiscent of points in Faraday and Stodart's papers. Thus, the writer of the article in question points out that while the reflecting power of silver has been largely used in the past in making, for example, searchlights and reflectors of various types, yet this metal has the disadvantage of tarnishing rapidly and requiring constant attention. On the other hand, platinum, palladium and rhodium "have before them a wide field as plating materials, both being corrosion and heat resisting to a high degree. Thus, taking the reflecting power of a highly polished silver mirror as 100, that of rhodium is 70, while platinum and palladium both range round about 60, with the added advantages of hardness and non-tarnishing. The electro-deposition of either of these metals on, for example, copper affords a plating free from all pitting or porosity, and of a far warmer and more beautiful appearance than the popular chromium finish of to-day. Alloys of the platinum group metals and coatings of the actual metals themselves have thus potential engineering applications which await development as soon as their supply at reasonable economic costs becomes available. In electrical engineering platinum contacts are far more effective and durable than any of the platinum substitutes, the use of which in the past has in the main been due to the relative scarcity and high cost of platinum itself."

The following is a list showing the fineness of the platinum group metals refined at Acton :—

	Per cent.
Platinum	99·93
Palladium	99·94
Iridium	99·97
Rhodium	99·70
Ruthenium	99·70
Gold	99·97
Silver	99·97

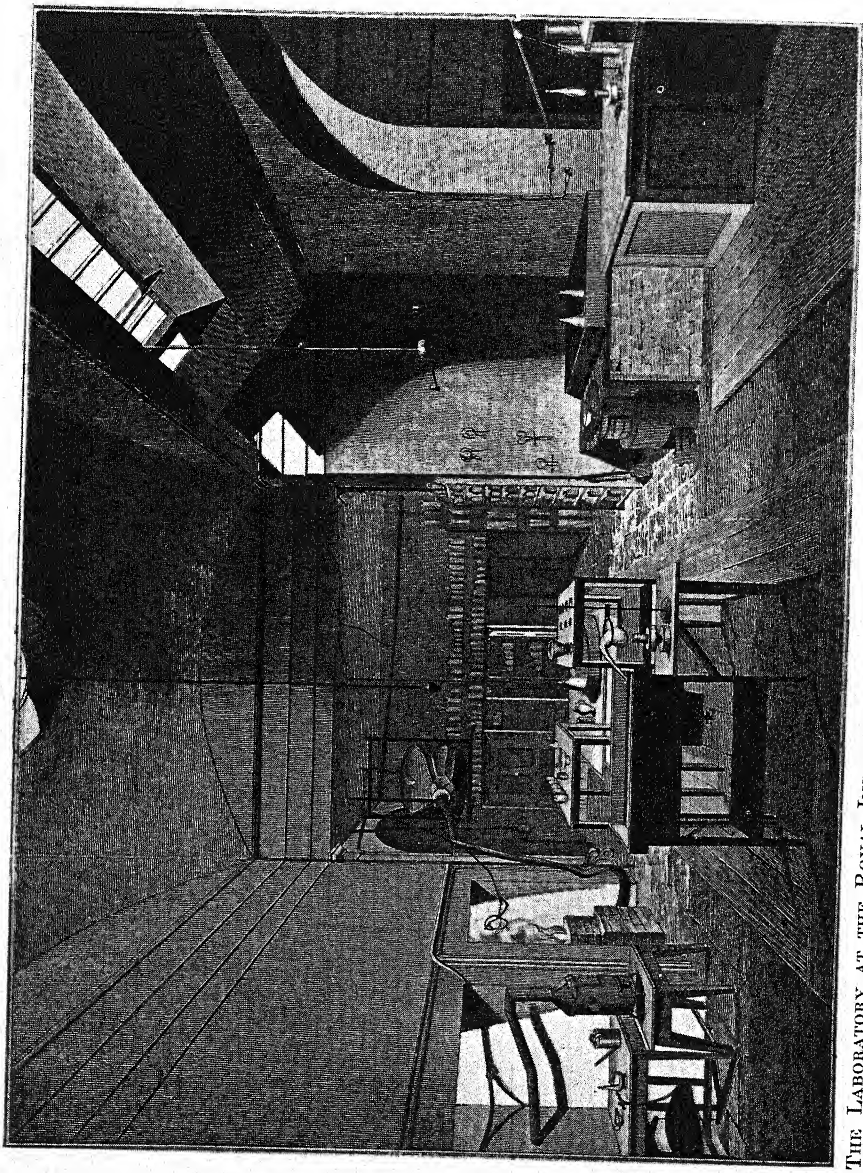
As an outcome of the improved practice resulting from the many researches carried out and in hand, considerable progress may be expected, including the cheapening of the prices of these important elements. It is expected also that these results will greatly widen the use of the platinum group of metals, including the special attention being devoted to the method of plating them on other metals.

CHAPTER VI

THE BIRTH OF ALLOY STEELS

From this and the following chapter it will be seen that Faraday's work on "steel and alloys" may fairly be regarded as representing the birth of systematic research on alloy steels. It was not, it is true, the opening of the era of practical utilisation of alloy steels on a large scale—that era has been said by eminent metallurgists to have opened with the author's discovery and invention of manganese steel, but the author freely acknowledges that Faraday forestalled him to the extent of more than half a century as regards deliberate research on an extensive series of alloys of steel. Faraday was the first to undertake such a research, hence, in that sense, his work may truly be said to mark the birth of alloy steels.

If this be acknowledged, as the author believes it must be, then the birthplace of alloy steels was the Royal Institution Laboratory, for it was here that Faraday conducted all his experiments and made all the specimens the full examination of which is described in the next chapter of this book. Similarly, Sheffield was the birthplace of alloy steels on a larger scale, for Faraday sent all his materials for the manufacture of alloys "in the large way" down to Sanderson's works at Sheffield. It was at Sheffield, too, that the firm of Green, Pickslay & Co. made cutlery and the fronts of stoves and fenders from certain of Faraday's alloys, as mentioned later in this chapter. It was at Sheffield that the author discovered and invented manganese steel, also silicon steel, followed by his further steel alloy researches between the years 1889 and 1915 with regard to the effect of aluminium, chromium, nickel, tungsten, cobalt, copper, titanium and molybdenum upon the metal iron. Thus, while the Royal Institution should be regarded as the birthplace of alloy steels on the laboratory and experimental scale, their first industrial application—tentative and temporary in Faraday's time, but enduring and ever increasing since the eighties of the last century—was in Sheffield. As a Sheffield man himself, the author is naturally proud of the fact that his native city has been so closely associated with this, as with so many other important developments in ferrous metallurgy.



THE LABORATORY AT THE ROYAL INSTITUTION AS IT WAS IN FARADAY'S TIME: FROM BRANDE'S "MANUAL OF CHEMISTRY," 1819.

[*To face p.* 90.

Credit Due to Faraday

It is really wonderful what Faraday accomplished when one considers the date at which he worked on steels, the very limited amount of information then available on the subject, and the poor means at his disposal for accomplishing the many difficult operations involved.

First and foremost, he set himself the problem of making and investigating an extensive range of alloys of steel with most of the then known elements which offered the possibility of being alloyed with iron. He is entitled to great credit for being the first to visualise and conduct a correlated series of researches of this kind. Then, having planned his work, Faraday overcame extraordinary difficulties in melting his materials and making his alloys with the equipment at his disposal in the basement of the Royal Institution. A " blast furnace hand worked " and the crucibles of those days formed poor facilities for dealing with such refractory materials as alloys of platinum and rhodium with steel, to mention only two of the alloys which he produced. His ingots, or rather " buttons," of alloy were left in the furnace to cool in the crucible. Forging them would not be an easy job, but it was accomplished. Some of the later and larger melts were, of course, prepared in Sheffield, and, no doubt, Stodart, whose business was to work steel for cutlery and surgical instruments, was able to forge some of these experimental ingots in his own workshop. Nevertheless, it is evident that Faraday did wonders with his own hands and with comparatively crude resources in the Royal Institution itself.

After very careful examination and consideration of records and papers covering the period 1797 to 1824, including, of course, the two papers by Stodart and Faraday, " Experiments on the Alloys of Steel made with a View to its Improvement," read in 1820 before the Royal Institution, and " On the Alloys of Steel," read in 1822 before the Royal Society, the author has no hesitation in saying that Table V., p. 164, represents alloys of steel actually produced and investigated by Faraday at the Royal Institution.

These specimens were undoubtedly produced by melting the ingredients in the experimental " blast furnace " situated in one of the basement rooms of the Institution. This equipment is fully described in Faraday's book *Chemical Manipulation* and referred to on p. 99 of this book. A general view of the laboratory is shown in Plate XXVI., reproduced from the Second Edition of Professor W. T. Brande's *Manual of Chemistry*, published by John Murray in 1821.

Always a leader, Faraday was greatly in advance of his time in regard to steel alloys. Neither the materials nor the means were available for full development of his ideas, and there was nothing like the present-day scope for special steels. In fact, even mild carbon steel had not yet come into its own; cast iron and wrought iron were the only ferrous materials used on any extensive scale. At the same time, the fact that Faraday's work was so far in advance of the requirements of his day should not cause us to overlook the fact that he was the first to commence the systematic exploration of the field of special steels.

Conditions under which Faraday Worked

Before going on to consider the several phases of Faraday's work in greater detail, it is instructive to examine the conditions under which he worked and the facilities at his disposal. The general state of knowledge concerning iron and steel at that time may be gathered from the notes in Chapter IV., and it is not necessary here to say more on this subject. We may, however, learn much from a study of the laboratory equipment and other facilities—or, from the modern point of view, lack of facilities—with which Faraday had to work.

In one respect Faraday enjoyed a special advantage. He had, as it were, Stodart at one elbow and Wollaston at the other. To Stodart he could turn for practical assistance in the forging and finishing of trial knives, razors, or other cutting instruments, for advice as to the requirements of the cutlery trade of those days, and for introductions to steelmakers if he desired them. On the other hand, he could and did obtain from Dr. Wollaston much assistance in the way of supplies of platinum and other special elements.

In other respects, however, Faraday had little enough at his disposal in the way of existing knowledge or facilities for such a difficult research as that on steels.

Apart from the limited amount of metallurgical knowledge available at the time when Faraday embarked on his steel researches, there was a complete absence of many pieces of apparatus now considered essential to the scientific examination of steel, such as mechanical testing machines, apparatus for metallographic examination, magnetic testing and so on. Many of the conveniences of life which we take for granted were still unknown. Gas lighting had been introduced in London a few years before (Westminster Bridge was lighted by gas in 1813), but it was by no means general, and the first really practical friction matches were made in England by John Walker, of Stockton-on-Tees, in 1827—three

years after Faraday discontinued his work on steel. Before matches became common, flint, steel and tinder were the ordinary means of making fire, but in a laboratory one could indulge in the luxury of a phosphorus bottle. In his *Chemical Manipulation*, p. 22, Faraday says :—

"For the eupyrion may be substituted the phosphorus bottle, made by stirring a piece of phosphorus about in a dry bottle with a hot wire ; the phosphorus undergoes partial combustion and forms a highly combustible coat over the interior : a common sulphur match rubbed against the inside of the bottle and drawn out into the air immediately flames ; or if it should not do so, a second stir with the hot wire, or two or three days' rest, will generally render the bottle a good one."

The satisfactory means of "getting a light" obviously depended on having means of heating a wire to begin with ! The author has given this quotation at length because it helps to bring home to us the extent to which the scientific investigator of a century ago was not merely unaided by modern facilities, but actually hampered by lack of common conveniences to which we are so accustomed that we rarely give them a thought.

Similar difficulties arose from the lack of all means of mechanical transport. Faraday describes the preparation of mixtures to be taken to Sheffield by coach for melting. There were no railways in those days. The famous Darlington and Stockton line had certainly not been opened and probably its construction was not even started.

Even by express coach service the journey from London to Sheffield occupied twenty-four hours, as witness the following copy of an advertisement appearing in *The Iris, or Sheffield Advertiser* of November 5th, 1822 :—

"JOHN LAMBERT & Co., most respectfully inform the Public in general, that they have reduced the Fares and Rates of Carriage to London as under.

"The Express leaves the Tontine Inn every day at Twelve o'Clock passing through Nottingham, Leicester, Northampton, Dunstable, &c. to the Bull and Mouth Inn, Bull and Mouth Street, London, where it arrives by Twelve o'Clock the following day, when Goods will be delivered immediately on arrival.

Inside Fare	£2	12	6
Outside	1	7	0
Small parcels	0	1	8
Goods per lb.	0	0	1½

Performed by

JOHN LAMBERT and Co.

Who will not be accountable for Passengers' Luggage, Plate, or any Goods above Five Pounds in value, unless entered as such and paid for accordingly."

A similar service from Sheffield to Birmingham was maintained by the *Royal Telegraph* coach, which completed the journey of eighty miles in nine and a half hours, and connected with coaches for "Bristol, Worcester, Warwick, Oxford and all parts of the West of England."

The use of iron instead of wood for ships did not become common until thirty or forty years later, and the era of steamships for mercantile purposes can be considered to date from about 1880, or sixty years after Faraday's experiments on steel alloys.

Cast iron and wrought iron were the chief ferrous materials of construction when Faraday's genius foresaw the importance of alloy steels. Puddled steel was known, but it was only used for comparatively few purposes. Cast steel was also used, being made by the crucible process introduced by Huntsman, but its manufacture was restricted to comparatively small quantities of the higher carbon steels, and its applications were almost entirely for tools, cutting instruments and similar purposes. It was nearly forty years later, in 1856, that Bessemer read his first paper at Cheltenham describing the art of producing the material known as Bessemer steel.

Examples could be multiplied, but it is almost impossible for us to form anything like a complete mental picture of the conditions existing about the time 1819–1824. Almost everything to which we are accustomed, specially in regard to steel, was then unknown—the picture consists mainly of a series of blanks! All the more honour to Faraday, who conceived a research in many respects fifty years or more ahead of his time, and with his own hands made so many alloys of steel of such varied and interesting qualities.

In a letter to his friend Professor G. de la Rive, Faraday gave a general summary of his researches on the alloys of steel and pointed out that he and Stodart carried on their experiments for two years under very laborious conditions, concluding by saying he hoped that "you (de la Rive) would applaud us for our perseverance at least." Still more ought we to applaud Faraday's perseverance, for to-day, with all the knowledge and resources which we now enjoy, it is difficult indeed to appreciate the full magnitude of the obstacles which he overcame. It should be here mentioned that Faraday was given much credit by the French, also Russian, authorities of that time with regard to his metallurgical investigations. His truly remarkable book *Chemical Manipulation*—probably the most detailed and lucid laboratory manual ever written, and one which might still be used with profit

by every student—shows how primitive were the resources at his disposal and what excellent use he made of them.

Faraday's Facilities Contrasted with Those of To-Day

It has already been stated that Faraday had nothing in any way comparable with the equipment and facilities of a modern laboratory to aid him in his researches. The significance of that fact may be better realised, perhaps, by taking a few actual examples to show the difference between conditions then and now.

In the first place, Faraday's chemical methods and equipment were very primitive as judged by modern standards. Quantitative chemical analysis was practically unknown, and the symbols and methods of expressing chemical reactions were still confused by the signs of the alchemists as shown on p. 15 of Chapter II. Now, however, chemistry is a precise science. The metallurgical chemist of to-day can separate and account for every element in even the most complex compounds and alloys, while using an extraordinarily small quantity of material for the purpose. No better example of this could be given than the remarkable data in Chapter VII. showing that in the 493 analyses made in this research on Faraday's steel and alloys, the total weight used up for these determinations represented only $6\frac{3}{4}$ ozs. of metal.

Microscopic investigation as practised to-day, using specially prepared and etched sections, was unknown in Faraday's time, though Faraday showed his appreciation of the importance of the structure of steel by examining it through a magnifying glass and probably by the microscope shown in Plate XXVIII. Spectroscopic and X-ray investigations, now of great and increasing importance as aids to metallurgical research, were then unknown.

The mechanical testing of steel and alloys a century ago was usually restricted to purely qualitative tests of brittleness, hardness and forgeability, using hammer, chisel and file, though Davy, in 1812, cited the tensile strength of a fine iron wire as referred to on p. 65. To-day the mechanical properties of any steel can be determined fully and accurately as regards tenacity, including elastic limit and yield point, also compressive and shear strengths, hardness, impact value, fatigue limit and other physical properties. Also, the work of Osmond, Arnold, H. le Chatelier, Roberts-Austen, Stead, Chevenard and others has enabled us to prepare pyrometric data, also heating and cooling curves, and to base valuable deductions thereon; while we have the advantages of electrical and magnetic testing apparatus of a very high order, far beyond anything known or available in Faraday's time.

Nor must the work of the metallurgical chemist be forgotten;

his part in metallurgy is one of the highest order. In an article by the author, which appeared in the *Daily Herald* of June 8th, 1931, as part of a special series in relation to Science in Industry, the chemist's share in the progress of metallurgical science is fully described. As there stated it is about 150 years since the study of steel by chemical methods began, for one of the earliest records of such a study is contained in a dissertation by Torbern Bergman, of the University of Upsala, published in 1781.

A little later followed the work of the French chemist Berthollet, who recognised that the differences in the varieties of iron were determined by the carbon contained therein. In 1827 Karsten separated from soft steel a compound of iron and carbon, thus preparing the way for later work by Sir Frederick Abel, F.R.S., who isolated the carbide compound now recognised as of fundamental importance in the metallurgy of steel.

The author would also mention Mr. Edward Riley, who in 1853 joined the staff of the Dowlais Ironworks as a chemist, and there in 1857 helped to carry out the first experiments on an industrial scale with the Bessemer process, which is still of prime importance in the steel industry; also Dr. John Percy, F.R.S., whose name appears prominently in this book. Then followed the world-renowned names of Messrs. Thomas, Gilchrist and Snelus, who effected a revolution in steel manufacture by the introduction of the basic process.

Amongst British metallurgical chemists may be mentioned the late Professor W. C. Roberts-Austen, Professor A. K. Huntington, Dr. J. E. Stead, F.R.S., and Professor J. O. Arnold, F.R.S. Much service has been rendered by Mr. F. W. Harbord, F.I.C., A.R.S.M., including that in his well-known book *The Metallurgy of Steel;* by Professor Henry Louis, M.A., B.Sc., Sir Harold Carpenter, F.R.S., Dr. W. Rosenhain, F.R.S., Mr. E. H. Saniter, Professor T. Turner, and many others.

Abroad may be mentioned Professors R. Akerman, S. Arrhenius, C. Benedicks, E. D. Campbell, A. S. Cushman, H. Egleston, G. Freminville, F. Giolitti, H. M. Howe, Zay Jeffries, A. Ledebur, F. F. Lucas, A. Pourcel, H. Moissan, Baraduc-Müller, A. Sauveur, D. Tschernoff, H. Wedding and others.

Facilities of the highest order are now available for the melting and preparation of steel whether in the crucible, open hearth, converter, or electric furnace, including the latest type of the latter, the high-frequency induction furnace. Faraday's equipment in these respects was limited to crucibles of variable quality, and a hand-blown " blast furnace " as described later in this chapter. He had nothing at all comparable with modern electrical and optical pyrometers for the convenient and accurate measurement

of high temperatures, and he appears to have made no attempt to measure the temperatures of fusion of his various alloys. He was, as shown on p. 98, aware of the importance of heat treatment and the general utility of pyrometers as then available, but, if he had wished to measure the melting points of steel alloys, the only means at his disposal would have been the " thermometer pieces " of clay devised by Josiah Wedgwood, which, whilst useful, at the best could only afford comparative data on an arbitrary scale, or the Daniell pyrometer, an apparatus which formed as the author shows elsewhere part of the equipment of the Royal Institution Laboratory. The many types of furnaces and pyrometers now available for the melting and heat treatment of steel and alloys find no parallel in the equipment available either to Faraday or to the Sheffield firms who made and used some of the alloys.

Curiously enough the high-frequency induction furnace, which is the latest type of equipment for melting refractory materials, is yet another practical application of Faraday's wonderful discovery of electromagnetic induction. This discovery was not made until some years after Faraday abandoned his researches on steel, and great advances had to be made in electrical technology before the discovery could be applied as it is to-day, but it ought not to be forgotten that we owe to Faraday the first systematic research on alloy steels, and the important discovery which led to the latest and best method of preparing alloy steels free from any possibility of contamination. When Faraday succeeded in preparing his specimen (No. 31/D.4, Table V.) containing only 0·07 per cent. carbon by means of his little " blast furnace " he performed an operation of much greater technical difficulty than is now offered by the melting of pure iron in a high-frequency furnace.

One other point, by no means the least important, deserves to be mentioned specially. To-day we have an easy and plentiful supply of pure metals and a wide range of ferro-alloys, which make it a comparatively simple matter for the experienced steelmaker to prepare any desired alloy steel. In Faraday's time, however, there was no source of supply of ferro-alloys, with the exception of spiegel—and even that was not used in this connection for Faraday never mentions the preparation of an alloy of steel with manganese, and none of his specimens examined by the author shows any evidence of the deliberate introduction of manganese.

Faraday's Pyrometers

Though, as mentioned above, Faraday had no means comparable with ours for the easy and accurate measurement of high tempera-

tures, he refers in his book *Chemical Manipulation* to the Daniell pyrometer, which depended for its action on the difference between the expansion and contraction of a platinum bar and a tube of black lead ware in which it was contained. These differences were indicated by the movement of an index connected to the bar over a circular scale attached to the tube. In an improved form of the instrument the scale was separate from the indicating part, so that the latter could be placed wholly in a fire or even immersed in molten metal. Faraday considered this pyrometer to be much superior to any other means then available for the measurement of high temperatures, but, with true prophetic insight into the course of future developments, he drew attention to "thermo-electric indications, founded on Seebeck's beautiful discovery." At that time, "the direct application of the method to the determination of the higher temperatures had not been made practical in the hands of an ordinary observer," but nowadays thermo-couples are used in countless thousands for the measurement of all temperatures up to the limits imposed by the melting points of the metals employed in the thermo-couples themselves.

Faraday foresaw the importance of pyrometric development and application, which in its turn, and quite apart from the work of the chemist, has been one of the means of helping to revolutionise steel practice whether as regards the actual production of the steel or its subsequent heat treatment.

The Wedgwood pyrometer brought out in 1782 was the first practical instrument for measuring high temperatures, and the next step in advance was the expansion pyrometer of Daniell in 1822. Subsequently the Siemens copper ball water pyrometer was evolved. These remained for a long time practically the only instruments available. Since that time the developments brought about have been through the introduction of the Siemens resistance pyrometer, the improved reliability of which type resulted from the researches of Professor Callendar and Professor Griffiths, and the thermo-electric pyrometer brought into successful operation by Professor H. le Chatelier. To all these pioneers we owe a great debt of gratitude. Still later were the valuable optical pyrometers, in the development of which H. le Chatelier also played such a leading part.

Faraday's Furnaces

One of the first questions that arises in considering Faraday's remarkable researches on steels, including alloys of steel with such refractory metals as platinum, is: How did he melt his ingredients?

Fortunately, there is a complete answer to this in his book *Chemical Manipulation*. Therein, he describes a whole series of furnaces consisting essentially of perforated black lead or earthen crucibles (forming the body or outer casing), burning charcoal or coke on a cast-iron grate, and provided with forced draught when the highest temperatures were required. He gives the most detailed instructions concerning the preparation of these furnaces, the location of the air holes and grate, the strengthening of the walls by binding wires, the arrangement of cowls and flues and the manipulation of bellows to intensify the draught and heat—in fact, such instructions as would enable us to build exact replicas of the furnaces he used. The manipulative hints given in his book leave no shadow of doubt that he was thoroughly familiar with the use of these furnaces at all heats up to the highest the crucibles would stand.

The following is Faraday's description of "a most excellent blast furnace, which has been in use for some years in the laboratory of the Royal Institution," and was evidently the one used by Faraday to melt and prepare his alloys of steel. The accompanying illustration Fig. 1 is from Faraday's own sketch of the furnace. He says :—

"It is sufficiently powerful to melt pure iron in a crucible in twelve or fifteen minutes, the fire having been previously lighted. It will effect the fusion of rhodium, and even pieces of pure platinum have sunk together into one button in a crucible heated by it. All kinds of crucibles, including the Cornish and the Hessian, soften, fuse, and become frothy in it ; and it is the want of vessels which has hitherto put a limit to its applications. The exterior consists of a blue pot eighteen inches in height, and thirteen inches in external diameter at the top. A small blue pot, of seven inches and a half internal diameter at the top, had the lower part cut off, so as to leave an aperture of five inches. This, when put into the larger pot, rested upon its lower external edge, the tops of the two being level. The interval between them, which gradually increased from the lower to the upper part, was filled with pulverized glass-blower's pots, to which enough water had been added to moisten the powder, which was pressed down by sticks, so as to make the whole a compact mass. A round grate was then dropped into the furnace, of such a size that it rested about an inch above the lower edge of the inner pot : The space beneath it therefore constituted the air-chamber, and the part above the body of the furnace. The former was 7½ inches from the grate to the bottom, and the latter 7½ inches from the grate to the top. Finally a horizontal hole, conical in form, and 1½ inch in diameter on the exterior, was cut through the outer pot, forming an opening into the air-chamber at the lower part, its use being to receive the nozzle of the bellows by which the blast was to be thrown in. The furnace being thus completed, the next object was to dry it gradually, that when used it might not be blown to pieces by confined aqueous

vapour; a charcoal fire was therefore made in it, and left to burn for some hours, being supplied with air only by the draught through the hole into the chamber beneath. When vapours ceased to be formed, the furnace was considered as ready for use.

"This furnace has always been used with a pair of large double bellows mounted in an iron frame, the former being raised upon a stool so as to bring the aperture of the air-chamber to a level with the nozzle of the bellows. The latter has generally been inserted in the aperture; for this and similar furnaces are of such depth, compared to their width,

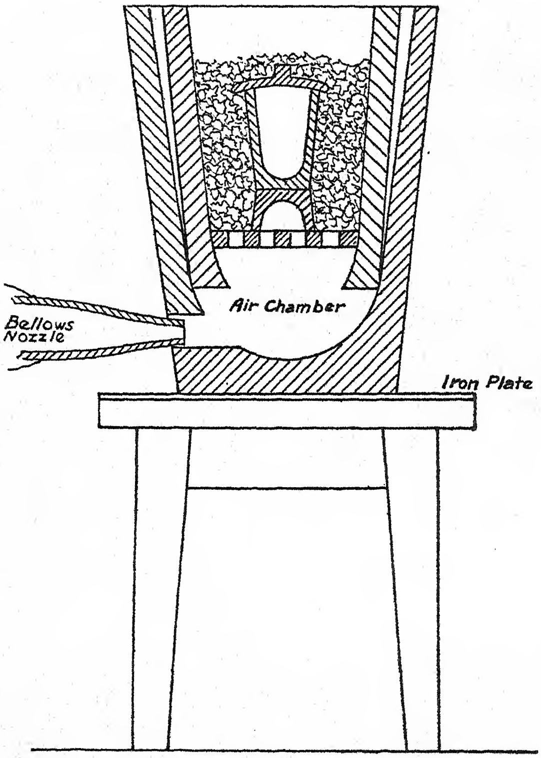


FIG. 1.—Faraday's Blast Furnace. ⅛th full size.

that when charged with a crucible and fuel, there is so much resistance to the passage of the air, when urged by a blast competent to create and sustain a vivid combustion, that a part returns by the side of the nozzle, if the aperture be left open. The bellows spoken of is far larger than necessary for the furnace described, and is rarely worked to one-third of its power; for otherwise the heat rises so high as to destroy the crucible, and the results are lost; it is, however, at all times advisable to have an abundant command of air.

"The heat produced by this arrangement is such, as at every violent operation, to cause the production of some slag from the melting of the inner surface of the furnace itself, where the combustion has been

most vivid. The slag, running down the interior, collects round the edge of the grate, and should be removed with a chisel and hammer, or with an iron rod, after each operation, that the grate may be clear and free from obstruction for the next process. When, in the course of time, the interior of the furnace is so far injured as to become thin and weak, it must be displaced, and the furnace restored to its original state, by the introduction of a new inside as before.

"The fuel to be used in this furnace is coke. Its consumption is very small, considering the heat that is obtained, in consequence of the short period of each operation. The superiority of the blast-furnace over the wind furnace * in many operations for which high temperatures are required, depends upon the rapidity of its action. It is requisite to employ this furnace in the open air, or under a well arranged vent, for an immense number of sparks, much flame, and a current of hot air are produced during its operation, which might occasion serious mischief in a room, unless the ceiling were at a considerable height, or guarded by a metal screen.

"In using a blast-furnace like the one described, some circumstances have to be considered relative to the method of applying the stream of air. If a small pair of bellows be used, the nozzle of which is considerably less than the aperture into which the air is propelled, then a much larger quantity of air is made to enter, if the nozzle be a couple of inches or more from the hole on the outside than if it be actually inserted; for, in the latter case, little more than the stream of air from the bellows is thrown through the furnace, whilst in the former a large additional quantity is propelled and drawn by the advancing stream, and carried with it; just, indeed, as happens with the blow-pipe jet of air where the flame and neighbouring atmosphere is drawn into the current formed by the propelled central stream. Hence if the bellows be small and the fuel not too compact, advantage may be taken of this circumstance, and the heat more highly raised and sustained than if the effect in question were unattended to.

"Priestley, and after him Lavoisier, proposed the application of oxygen to furnaces, to increase the rapidity of combustion, and consequently the intensity of heat: but it will evidently be unnecessary to employ it whilst furnaces in which common air is used continue to be more than equal to our means, in consequence of the limit put to their application, by the inadequacy of the vessels we possess to resist higher temperatures."

The more one reflects upon the remarkable acuity of observation and powers of deduction displayed by Faraday throughout this truly scientific and practical work, the more one regrets that he had none of the special facilities now at our disposal. With them there would have been no bounds to the discoveries he might have made. One is tempted to regret that he lived so soon and that so rare a combination of zeal, ability and intellect existed before circumstances were such as to permit the results which might now be

* A less powerful type of furnace also described in Faraday's *Chemical Manipulation*; he used the "blast furnace" for his steel researches.

obtained. Actually, of course, Faraday's industry, skill and genius found full employment. He discovered much that was unknown before, and laid many of the foundations on which later workers built.

By a strange coincidence, Faraday's last public address, on June 20th, 1862, was a masterly explanation of the Siemens regenerative furnace, at that time a new invention. The paper dealt primarily with the application of this furnace to the melting of glass, but it also went further, dealing with the theory of the furnace with all the lucidity and scientific insight for which Faraday was famous. Thus, at the end as well as at the commencement of his active career we find Faraday speaking and writing with evident authority upon the construction and operation of what may be regarded as typical examples of the best furnaces available for specific purposes at the respective dates, some forty years apart.

The lecture of 1862 mentioned that Siemens had combined the two principles of gas heating and heat regeneration, and applied them successfully to a great variety of cases, including potters' kilns, enamellers' furnaces, zinc distilling furnaces, iron puddling furnaces and glass furnaces. The glass furnace specially described had an area of 28 feet long and 14 feet wide, and contained eight open pots each holding nearly 2 tons of material.

Although the science of thermodynamics was still in its infancy at the time of the lecture, the statements dealing with certain aspects of the heat balance were remarkably accurate. Julius Thomsen had only commenced his varied and important researches into heats of reaction in 1853. Berthelot's contributions were not to commence until 1865, three years after this lecture was delivered. Faraday could only therefore be in possession of the data which had resulted from Thomsen's work. In regard to this aspect of the communication it is interesting to note that the distribution of heat is defined in terms of a temperature scale, thus, in the gas producer "carbon burnt perfectly into carbonic acid . . . would evolve about 4000° of heat, but if burnt into carbonic oxide, it would evolve only 1200°. The carbonic oxide, in its fuel form, carries on with it the 2800° in chemical force, which it evolves when burning in the real furnace with a sufficient supply of air. The remaining 1200° are employed in the gas producer in distilling hydro-carbons, decomposing water, etc."

We should speak to-day of the "cold gas" efficiency of the producer. It approximates to the value of the ratio 0·70 given by Faraday. Again, it is stated, "the whole mixed gaseous fuel can

evolve about 4000° F. (2200° C.) in the furnace, to which the regenerator can return about 3000° F. (1670° C.) more." Actually the calorific intensity of a producer gas flame, with regeneration temperatures of 1000° C. and the most perfect mixing, is 2500–2600° C., and, without regeneration, 1750° C. The true flame temperature, by reason of the energy radiated from the flame is probably not above 1850° C., and the maximum temperatures attained in regeneration of the order of 1400° C. If one considers, however, that the optical pyrometer had not been developed, and that the interpretation of a heating intensity had to be based on such calorimetric measurements of the heat of combustion as existed at that time, together with what amounted to an approximate knowledge of specific heat, it is remarkable that the values given by Faraday should approach so nearly to the true exchanges of heat occurring in the operation of the Siemens regenerative furnace.

Faraday's Crucibles and Refractories

In Faraday's time the available refractory materials placed a limit on the temperatures which he could use in his experiments. Greater heat could be attained in his simple " blast furnace " than the best crucibles at his disposal could withstand. However, he displayed the utmost ingenuity and resource in utilising imperfect materials to the best advantage, so as to subject specimens to great heat while avoiding undue destruction of crucibles and, specially, guarding against contamination of metal by fuel and slag. The precautions he took to this end may be realised from perusal of the chapter on Crucible Operations in his book *Chemical Manipulation.*

He distinguishes between the ordinary crucibles of the times as relatively soft and unable to withstand the action of fluxes and temperatures higher than bright red heat; Hessian crucibles, much harder and altogether more resistant to heat and fluxes; and Cornish crucibles, of even better quality. In addition, there were " blue pots " or black lead crucibles made of a mixture of coarse plumbago and clay; these were generally of larger size and were superior to the ordinary crucible, but could not be used where their iron and carbon content would be injurious. Faraday was well aware of the advantages of charcoal crucibles or charcoal-lined crucibles for certain operations of reduction; and " on particular occasions," presumably where additional strength was required at very high temperatures, he used double crucibles made by placing one inside a larger one, and filling the space between with Stourbridge

clay. He refers also to the advantage, in some circumstances, of fitting a platinum crucible inside a Cornish one and, in fact, he was evidently thoroughly acquainted with every device and expedient for making the best use of his crucibles.

Notwithstanding all his care, the temperatures he reached were sufficient to soften his crucibles and even to cause their complete collapse. Having evidently learnt by painful experience, he makes various useful suggestions for relieving the crucible of mechanical load in the furnace and for protecting its contents from contamination and loss. He had discovered, and warns the student against, the risks of damage to crucibles by the corrosive action of various fluxes and compounds, and he was equally aware of the dangers of contaminating the contents of the crucible by absorption from the latter. Thus he refers in one place (*Chemical Manipulation*, p. 292) to the fact that either wrought iron or cast iron heated intensely in an earthen crucible will be found to have combined with silicon and he says, in some cases, with aluminium. There can be no doubt that he obtained much of his knowledge concerning the proper and advantageous use of furnaces and crucibles in the course of his investigations on alloys and, in securing this information alone, his time was far from wasted. If we had to rely upon similar furnaces and crucibles to-day we could take Faraday's advice as being entirely sufficient to guide us to the best possible results.

How Faraday Prepared His Alloys

A clear insight into the methods Faraday used in preparing his specimens of steel alloys can be derived from the following extracts (*Chemical Manipulation*, pp. 296–299) :—

"The utmost heat that can be given to a crucible is to be attained in the laboratory by such a blast furnace as has been already described * : the fuel being coke, or coke and charcoal. When of the dimensions specified, it will heat a crucible three inches and a half high, and two inches and three-quarters in its upper diameter, very highly ; and one not more than one inch and three-quarters diameter at the top, intensely. To acquire the most powerful heat, the crucible should be raised about one and a half or two inches from the grate, and covered with at least the same depth of fuel. Hence arises a necessity for supports and covers, capable of resisting intense temperatures. The best supports would be crucibles made of the Cornish or Hessian clay, of a cylindrical form, from one and a half to two inches in height, and from half an inch to an inch internal diameter ; the closed end being put upon the grate, and the bottom of the crucible on or into the aperture above, where it would

* See p. 99 of this book.

be steadily retained. But in the absence of such supports, recourse must be had to Cornish or Hessian crucibles, and one being selected with a flat bottom, it must be placed upside down, with the mouth upon the grate. From the irregular form of the bottoms of these crucibles and the necessity of choosing them as narrow as possible, that the fuel may be close to all parts of the crucible to be heated, the latter is necessarily, when simply placed upon the stand, very tottering; it is, therefore, generally advisable to lute the crucible and stand together with a little Stourbridge clay, a small portion being put between the two surfaces, and more at the side, so as in fact to make the two vessels into one, their bases being attached together. Such luting must be well dried for a day or two before it is placed into the furnace.

"With respect to covers, the arrangement is more difficult, in consequence of the absence of those necessary accompaniments to Hessian crucibles, and the uncertainty attending the supply of them with Cornish crucibles. Suppose that iron or steel is to be heated without contact of carbonaceous or extraneous substances of any kind. A common English cover will not answer the purpose, because it will melt and run into the crucible. A larger crucible of the same kind may be turned over it, and luted at the edges; but this inconveniently increases the size of the mass to be heated, which when the highest temperature is required, should be as small as possible. A smaller crucible of the same kind may be inverted and put *inside* the other, and the interval filled by a luting of Stourbridge clay; but the heat contracts the lute, the fissures of which may receive particles of fuel and slag. This is the more probable, because in all cases of a blast in the surface from below upwards, there is an eddy in the stream of air above the crucible, which stands as a fixed obstacle in the current, and which causes the return and accumulation of numerous small particles upon the top.

"The method that has been found to answer best, is to beat up some Stourbridge clay with water into stiff paste, to make it into a cake the fourth of an inch thick, to put it over the top of the crucible, to press it down with a common English cover of proper size, so as to force a cake of the damp clay into the crucible, and cut off the excess by its edge, and then to finish by luting the edge of the cover and the side of the crucible together. This is to be done before the crucible is luted upon its stand, and the whole is to be well dried previous to being used. When heat is applied, the internal cover of lute becomes baked, and though it diminishes in size, yet, from the form of the crucible, it seldom sinks down to the charge; and if the English external cover soften and fuse, it is still supported on the former, and generally serves to keep out impurities.

"When the crucible is of charcoal, or is lined with charcoal, and consequently has a charcoal stopper inside, the common cover may be put directly over it and luted; and even in plain crucibles, when charcoal is not injurious, an internal cover of it, formed out of one or several pieces, may be used instead of the plate of lute, and the ordinary cover then put over it.

"The furnace being clean and in order, and the crucible with its luted cover and stand dry, the latter is to be placed steadily on the grate of the furnace; a few pieces of lighted charcoal are to be dropped in and covered by cold charcoal to the depth of two or three inches, and the whole left until the combustion has spread amongst the fuel; the air will find sufficient access through the aperture beneath. When the crucible becomes warm, coke is to be added so as to cover it, and the temporary flue is to be adjusted, to assist the draught. When the fuel is nearly red hot an inch or two below the surface, more coke is to be added until it rises about two or three inches above the crucible, the flue is then to be replaced, and the combustion to proceed until the crucible itself is red hot. This will occupy perhaps an hour, and require attention only at the short intervals when coke is to be added. The course described is adapted to the object of raising the heat steadily and gradually to redness; it may be well to explain, that the coke should not be put on until the crucible has been somewhat warmed by the charcoal, to prevent the deposition upon it of the water driven from the fuel. Having attained a red heat, the flue must be removed, the bellows applied, slowly at first, and more powerfully as the heat rises, until the highest point required, or that is possible, be attained.

. . . . . .

"When very high temperatures are required, as in the fusion of platina or rhodium, the crucibles become so soft as to sink and fold like leather, and the results are often lost. This is sometimes due in part to the pressure of the fuel upon the crucible, and may be prevented by hanging a shelter over it. A long narrow English pot, having a mouth a little larger than the crucible to be heated, is to be selected, and a hole made through its bottom; by passing an iron rod with a hooked end through this hole, the pot may be suspended in an inverted position over the crucible and within half an inch of it, thus preventing the contact of the fuel with its top. Care will be requisite that the expansion of the rod and vessel, as the heat rises, should not cause the latter to press upon the crucible. A great depth of fuel is, on these occasions to be preserved in the furnace round the shelter, to compensate as much as possible for its effect in diminishing the temperature; and this, with a little more than common application of the bellows, is always sufficient for the purpose. In this way many crucibles and their contents have been saved, which, from the average of experiments without the shelter, there is reason to believe would have been lost.

. . . . . .

"In making alloys, the metals are to be well agitated together; for as some cases, even when apparently miscible and well mixed, there is, as Mr. Hatchett and others have shewn, a remarkable tendency to separation.* In the preparation of alloys, and the fusion of some metals, it is advantageous to cover the surface of the metal with pieces of charcoal, to prevent oxidation. In these cases a loose cover should be put on after the charcoal, to hinder the access of air, and prevent combustions as much as possible."

* *Phil. Trans.*, 1803.

Nothing could be more convincing and impressive than the minute description of procedure and precautions given in every paragraph of this extract—and the same may be said of the whole treatise from which it is taken. One stands in awe and admiration of Faraday's powers. He was a master indeed and one feels a sense of great humility in studying his writings, coupled, however, with the certainty that he would desire no such feelings in his readers, for his obvious intent was to help and smooth the path for others, not make any display of superior wisdom or ability.

From Faraday's own description of the manner in which his crucibles were entirely embedded in coke in his "blast furnace," it is easy to understand why he allowed, or at any rate in most cases, his alloys to cool in the crucible. The difficulty was to prevent the crucible from collapsing during the operation of melting, and it would certainly have been most difficult to remove the surrounding coke and lift out the crucible with its molten charge. The first forms of his specimens would therefore be (*a*) ingots or "buttons" of metal, these being subsequently forged into the form which the author ventures to call (*b*) blooms, (*c*) billets, (*d*) finished bars, as shown in Plates XXIX. and XXX. This is not an unimportant point, because it shows that Faraday, in his usual orderly fashion, rightly proceeded by the stages mentioned.

Materials Used by Faraday

From what has been already said it will be understood that practically all Faraday's alloys were produced in the crucible and could be well termed crucible cast steel. They were melted in the small "blast furnace," at the Royal Institution, which might be considered similar to the Sheffield crucible or pot melting furnaces.

As to the basis of the material he used and to which he added the desired special elements, the ordinary Sheffield practice still in use, though on a smaller scale than formerly, is to melt crucible cast steel from Swedish or other bar iron of high purity which has been previously cemented. Such material is known as :

		Carbon.
Spring temper		0·50 per cent.
Country temper		0·625 ,,
Single shear		0·75 ,,
Double shear		1·00 ,,
Steel through	(outside)	1·25 ,,
,, ,,	(centre)	0·89 ,,
Hard		1·35–1·50 ,,

In certain cases, but these are comparatively few, the pure bar iron not cemented is also used for melting and the desired percentage of carbon obtained by adding charcoal or carbonised pig iron of pure character. Such materials are melted in the crucible, then poured into small ingots, 2½ to 5 or 6 inches square, or even larger. The author has seen ingots weighing no less than 60 tons each for gun tube purposes, being poured from crucible cast steel.

The metals and non-metallic substances which Faraday stated he employed when making his steel and alloys are twenty in number. Arranged alphabetically in groups they are as follows :—

Metallic Elements : Thirteen in number, seven being noble metals :

1. Chromium.
2. Copper.
3. Gold.
4. Iridium.
5. Iron.
6. Nickel.
7. Osmium.
8. Palladium.
9. Platinum.
10. Rhodium.
11. Silver.
12. Tin.
13. Titanium.

Non-Metallic Elements : Three in number :

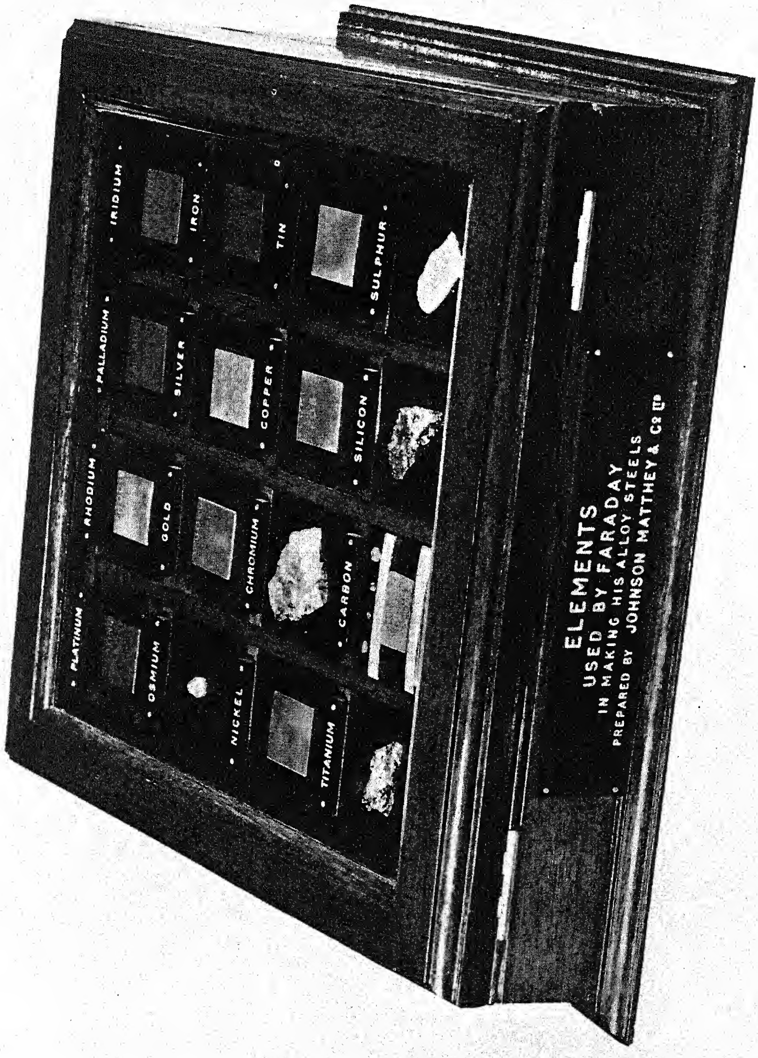
14. Carbon.
15. Silicon.
16. Sulphur.

Other Ferrous Substances : Four in number :

17. Wootz or Indian steel.
18. Carburet of iron.
19. Alumine alloy, so termed by Faraday in 1820, in imitation of wootz, also described as damascene steel. (Davy spoke of the added element as Aluminum.)
20. Meteoric iron.

Tabulation of the Above.

(*a*) Metallic elements .	13	(*a*) Noble metals . .	7
(*b*) Non-metallic elements .	3	(*b*) Ordinary metals .	6
(*c*) Other. . . .	4	(*c*) Non-metallic elements	3
		(*d*) Other . . .	4
	20		20



SPECIMENS OF THE SIXTEEN ELEMENTS EMPLOYED BY FARADAY IN MAKING HIS "STEEL AND ALLOYS."
This exhibit was kindly prepared for the author by Messrs. Johnson Matthey & Co. Ltd.

[*To face p.* 108.

During the Faraday Centenary Celebrations, through the aid of Messrs. Johnson, Matthey & Co., the author was able to exhibit at the Royal Albert Hall in an interesting showcase alongside the original Faraday steels arranged by him, specimens of each of the sixteen elements employed by Faraday in making his many and varied "Steel and Alloys." * Plate XXVII. represents in the showcase these specimens including the precious or noble metals, kindly lent to the author by Messrs. Johnson, Matthey & Co., for this historic exhibit.

Of the alloy additions previously mentioned the following have been actually determined by the author to be present in the various specimens of Faraday's steels examined by him: Carbon, chromium, nickel, copper, gold, iron, platinum, rhodium, palladium, silicon, silver and sulphur. The elements iridium, osmium, titanium and tin, although stated to have been used, were not found in any of the specimens examined, but these only represented a small portion of the total number of ordinary steels, alloy steels and other ferrous substances prepared by Faraday. The element palladium was found to be present in a considerable percentage (22·70 per cent.) in one of the Science Museum specimens, full particulars of which are given in Table XVIII.

Although several specimens of Faraday's "steel and alloys" contain a very low percentage of carbon, one containing only 0·07 per cent. (Specimen No. 31/D.4, Table V.)—a marvellous production for that early date—it will be seen from the analytical data presented in Tables V. and VII., and fully discussed in Chapter VII. that most of the specimens contain from 0·6 to 1·5 per cent. carbon. The difficulty of obtaining low carbon steel at that time must be borne in mind when considering Faraday's work.

Absence of Manganese

While on the subject of the metals used by Faraday in the preparation of his steels and alloys, special reference must be made to the fact that he never even mentioned manganese in his papers dealing with these researches. In the various analyses made by the author, the minimum amount of manganese found in Faraday's specimens was 0·04 per cent. and the maximum 0·07 per cent. In other words, the steels examined showed little more than a trace of this element, and in no case is there evidence that it had been added.

This omission is rather remarkable because Davy had experi-

* The physical constants of the elements employed by Faraday are given in Table XXVII. in Appendix II. The author believes his readers will find this of considerable service. The melting points are all based on the latest determinations.

mented with the metal manganese, or manganesum,* as he called it, and Faraday was well aware of its existence, for he read a paper on the "Separation of Manganese from Iron" before the Royal Institution in 1819. Also, the material termed spiegeleisen, or specular cast iron, a combination of manganese and high carbon, was well known, in fact it had probably been made in the Middle Ages, for there are mines in existence which have been worked for centuries past for the spathic ores from which spiegel is prepared.

Although the importance of manganese in relation to the production of industrial steels was entirely unknown in Faraday's time, and it apparently did not occur to him to investigate the effect of alloying this element with steel, nevertheless he had paid some attention in his chemical laboratory to the converse problem of separating it from iron.

It appears that Josiah Marshall Heath, who was much interested in steel, brought back wootz ore from India in 1826, that is, about two years after Faraday's last recorded experiments on steel alloys. It was not, however, until some years later that he brought out his invention regarding manganese additions, although Reynolds in 1799 patented the use of manganese oxide for steel manufacture. Heath was probably the first to discover and show the importance of the use of manganese as applied to ferrous metallurgy, and until then, strange as it may appear to us to-day, manganese had not been used in steelmaking. Neither crucible cast steel nor puddled steel required its use, but the art of steel manufacture was revolutionised when the influence of this remarkable metal manganese was discovered, that is its wonderful power of deoxidising or combining with oxygen and passing away in a fluid slag, also its influence as an alloying element on the working properties of steel at a red heat and higher temperatures even when present in small quantities. Silicon and aluminium remove oxygen more easily than manganese, but they do not pass away readily in the slags produced or when alloyed in small proportions do not appear to have a similar and beneficial effect on the working properties of the steel at a red heat or a higher temperature.

Without the use of manganese it would not be possible to manufacture the mild (0·10 to 0·25 per cent. C.) or medium (0·30 to

* Davy applied the term *manganese* to the oxide, that is, to "manganesum united to oxygen." He refers to "two definite combinations of manganesum and oxygen, one dark olive, one brownish black," and, as regards "manganesum" itself, he says it was first procured in pure form by Kain and Gahn between 1770 and 1775, that it is very brittle and of hardness nearly that of iron, that its sp. gr. is 6·850, and that it requires a higher degree of heat than iron for its fusion.

0·60 per cent. C.) steel of to-day, now used in such immense quantities. Of the 119 million tons of steel made during the year 1929, representing the world's present peak of output, by far the greater portion, probably nearly the whole of this, required the use of manganese, chiefly in the form of ferro-manganese. Considerable quantities of manganese are used in the production of the special alloy steel known as manganese steel, discovered and invented by the author, but the tonnage is, of course, comparatively small. This steel was fully described in his original paper on " Manganese Steel " to the Institution of Civil Engineers in 1888. The author has also more recently given a full account of the history of and the part played by manganese in its general applications to steel in his paper presented to the Iron and Steel Institute in 1927, entitled " The Metal Manganese and its Properties: also Ores and the Production of Ferro-Manganese and its History." Even with all our modern resources, no satisfactory substitute has been found to take the place of manganese in the production of steel of ordinary qualities. This fact was of serious importance to Germany during the Great War, when that country was cut off from normal supplies of manganese and various " substitutes " were tried without success. We were amply supplied with manganese ores and there was no shortage, moreover we were able to assist our Allies. It is a striking fact that the U.S.A., notwithstanding its wonderful mineral wealth has so far not found suitable or rich manganese ore in sufficient quantities, and this applies to Great Britain, though fortunately manganese supplies in large quantities are available in India, South Africa and elsewhere in the British Empire.

The author has dealt with this matter at some length because it is important to recognise that Faraday's alloys of steel and iron were of such different character from those of to-day, partly because of the absence of the metal manganese. Consequently he was driven to produce high-carbon steels of the type of those produced in the crucible, and known in those days as Huntsman's crucible cast steel.

Faraday's Own Account of Alloys of Steel

The first paper by Stodart and Faraday, was presented to the Royal Institution (published in the *Quarterly Journal of Science*, ix., 319, date 1820), and was entitled " Experiments on the Alloys of Steel, made with a View to Its Improvement." This title alone is sufficient justification for all the work which the research called for and involved, moreover it is in accordance with Faraday's

customary habit of undertaking investigations on the broadest possible basis. It was owing to this attitude of mind, no less than his close observation and accurate reasoning, that he was able to make so many important discoveries. Knowing how uncommercial was Faraday's outlook on life, we cannot doubt that he regarded his steel researches primarily from the standpoint of pure research; in other words, he would seek for and welcome every scrap of fresh knowledge, whether or not it had any obvious "practical" importance. At the same time, from his association with Stodart in this work, he would learn of certain improvements desirable in steel from the standpoint of the maker of surgical and other instruments, which improvements might fitly be made the practical object of the research.

Fortunately for us who have examined the specimens which he left behind him, Faraday * gave a clear statement of the particular directions in which it was hoped to improve steel by alloying. The opening words of the paper are :—

> "In proposing a series of experiments on the alloys of iron and steel with various other metals, the object in view was twofold: first, to ascertain whether any alloy could be artificially formed better, for the purpose of making cutting instruments, than steel in its purest state; and second, whether any such alloys would, under similar circumstances prove less susceptible of oxidation. New metallic combinations for reflecting mirrors were also a collateral object of research."

In other words, improved cutting steels and rust-resisting steels were the primary object, and it was hoped also to find a good material for mirrors. *Primâ facie* evidence of a certain measure of success in both directions is to be found in the fact that in later years Faraday occasionally presented to friends "razors made of his own special steel"—he would not have done this unless they had been reasonably satisfactory. The author's tests on two of Faraday's razors and on others of that period are described on p. 237. Again, a number of Faraday's specimens in the box stored at the Royal Institution, notably specimen No. 39 B/D12 B, Table V., were found to be brightly polished and quite free from any trace of rust after more than a hundred years, but it must be remembered that these specimens had not been submitted to severe tests such as outside exposure to the weather. Such steels,

* It would be more accurate here to say "Stodart and Faraday," the paper appearing under the joint names, but there can be no reasonable doubt that, whatever assistance Stodart may have given Faraday in the matter of practical advice, the paper is entirely in Faraday's words. In all probability the observations and deductions are equally his.

however, obviously offered some possibilities as mirrors in the days before silvered glass mirrors of modern type.

The special attention paid to the investigation of alloys of steel with the metals rhodium, palladium, osmium, iridium and platinum, all in the eighth group of the periodic classification of elements, was certainly on a definite scientific plan, though, of course, the precise form of that classification was not discovered until many years later by Mendeléef and others.

It is unnecessary here to reproduce the full text of Stodart and Faraday's papers, but a useful purpose will be served by giving a brief abstract of them. From this will be seen the remarkable grasp Faraday had of his subject and the extremely able manner in which he dealt with it, bearing in mind the conditions of available knowledge and facilities under which he worked. From this point of view, and in relation to the specimens which have survived to the present day, the following points from the first (1820) paper are specially interesting :—

The subject (alloys of steel) was new and opened into a large and interesting field. Almost an infinity of different metallic combinations may be made according to the nature and relative proportions of the metals capable of being alloyed.

From his analysis of wootz or Indian steel,* Faraday concluded that the excellent qualities of this material, and its property of showing a damascened surface when etched with acid, were due probably to the combination of steel with the metals of the earths alumine (alumina) and silex (silica). By making an alloy rich in alumina and using small proportions of this with "good steel," Faraday made a specimen which had "all the appreciable characters of the best Bombay wootz." From the fact that wootz always gave a damasked surface, although repeatedly fused and forged, he concluded that this property was due to crystallisation and not to mere mechanical mixture of two substances acted on unequally by acid.

From experiments made with alloys of iron (horseshoe nails) with 3 per cent and 10 per cent of nickel, in imitation of various specimens of meteoric iron, Faraday concludes that "nickel, when combined with iron, has some effect in preventing oxidation, though certainly not to the extent that has at times been attributed to it. It is a curious fact that the same quantity of nickel alloyed with steel, instead of preventing it rusting, appeared to accelerate it very rapidly."

Platinum and rhodium alloyed with iron did not appear to possess any very interesting properties, and "the alloys of other metals with iron, as far as our experience goes, do not promise much usefulness."

The results are very different when steel is used †; "it is only,

* See p. 83.

† In other words, Faraday noted the very important influence of carbon in alloy steels.

however, of a few of its compounds that we are prepared to give any account. Together with some others of the metals, the following have been alloyed with both English and Indian steel, and in various proportions: platinum, rhodium, gold, silver, nickel, copper and tin.

"All the above-named metals appear to have an affinity for steel sufficiently strong to make them combine: alloys of platinum, rhodium, gold and nickel may be obtained when the heat is sufficiently high. This is so remarkable with platinum that it will fuse when in contact with steel, at a heat at which the steel itself is not affected."

The results of the experiments with various alloys are then given in the Royal Institution paper in great detail, both positive and negative, successful and unsuccessful results being recorded. All the experiments covered by the Royal Institution (1820) paper were confined to small quantities of the metals, seldom exceeding 2000 grains in weight and, while admitting "that the operations of the laboratory are not always successful when practised on a large scale," Faraday says "there does not, however, appear to be any good reason why equal success may not attend the working on larger masses of the metals, provided the same diligence and means are employed."

Further results are recorded in the later and even fuller paper presented by Stodart and Faraday to the Royal Society on March 21st, 1822.* In this paper, the authors acknowledge their indebtedness to Dr. Wollaston, who assisted them in every stage of their progress and "furnished all the scarce and valuable metals . . . with a liberality which enabled us to transfer our operations from the laboratory of the chemist to the furnace of the maker of cast steel."

Accordingly, experiments proceeded on a much larger scale at Sheffield, and no doubt the ingots there produced were the first to be used for the commercial production of alloy steel articles. No evidence can be discovered as to the quantity of such articles produced or the period for which their manufacture was continued, but from the letters reproduced on p. 133 there can be no doubt that Faraday's alloy of steel with silver was used to some extent and for some time by Green, Pickslay & Co. in the manufacture of cutlery, stove fronts and fenders; a certain number of razors were made, probably of rhodium steel. These articles, for reasons which it is easy to appreciate, did not find any extensive or continued sale; nevertheless, *they were the first commercial products deliberately made from alloys of steel*, and, in this sense, they represented the commencement of the age of alloy and special steels.

* *Phil. Trans.*, 1822, p. 253; also *Phil. Mag.*, vol. LX., p. 363.

The Royal Society paper (1822) by Stodart and Faraday is mainly concerned with particulars of the large-scale experiments and with the corrosion-resisting properties of various alloys, but it opens with a significant passage which runs as follows :—

" The alloys of steel made on a small scale in the laboratory of the Royal Institution proving to be good, and the experiments having excited a very considerable degree of interest both at home and abroad, gave encouragement to attempt the work on a more extended scale ; and we have now the pleasure of stating that alloys similar to those made in the Royal Institution have been made for the purpose of manufacture ; and that they prove to be, in point of excellence, in every respect equal if not superior to the smaller productions of the laboratory. Previous, however, to extending the work, the former experiments were carefully repeated, and to the results were added some new combinations, namely, steel with palladium, steel with iridium and osmium, and latterly, steel with chromium. In this last series of experiments we were particularly fortunate, having by practice acquired considerable address in the management of the furnaces, and succeeded in procuring the best fuel for the purpose."

The authors go on to say (and this statement, be it remembered, is in the light of a further two years of strenuous research, from 1820 to 1822) that " the metals that form the most valuable alloys with steel are silver, platinum, rhodium, iridium and osmium, and palladium. All of these have now been made in the large way, except indeed the last-named. Palladium has, for very obvious reasons, been used but sparingly."

The work at Sheffield was done under Faraday's instructions, but not under his personal supervision. Concerning this, the Royal Society paper says :—

" In making the alloys on a large scale, we were under the necessity of removing our operations from London to a steel furnace at Sheffield ; and being prevented by other avocations from giving personal attendance, the superintendence of the work was consequently entrusted to an intelligent and confidential agent. To him the steel, together with the alloying metals in the exact proportion, and in the most favourable state for the purpose, was forwarded, with instructions to see the whole of the metals, and nothing else, packed into the crucible and placed in the furnace, to attend to it while there, and to suffer it to remain for some considerable time in a state of thin fusion, previous to its being poured out into the mould. The cast ingot was next, under the same superintendence, taken to the tilting mill, where it was forged into bars of a convenient size, at a temperature not higher than just to render the metal sufficiently malleable under the tilt hammer. When returned to us, it was subjected to examination both mechanical and chemical, as well as compared with the similar products of the laboratory. From the external appearance, as well as from the texture of the part when

broken by the blow of the hammer, we were able to form a tolerably correct judgment as to its general merits ; the hardness, toughness, and other properties were further proved by severe trials, after being fashioned into some instrument or tool, and properly hardened and tempered."

It was probably here, in fashioning the steels into some instrument or tool and properly hardening and tempering it, that Stodart was able to give Faraday most assistance, either personally or by placing the work in the hands of practical smiths and cutlers.

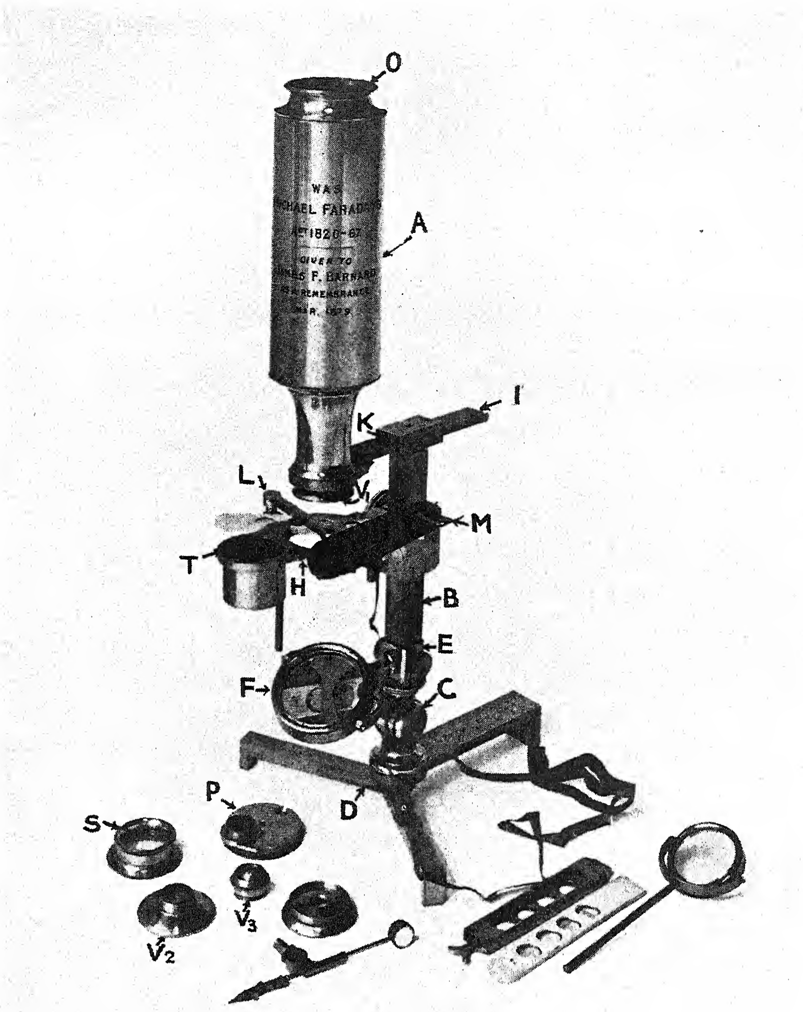
The difficulties of Faraday's position are revealed by the last-quoted paragraph above. The large-scale work was necessarily done under the supervision of an agent, who, however conscientious and able he might be, could only obey instructions. Faraday himself could make no fresh discoveries and observations while the work of melting, pouring and forging was being done more than 150 miles away. Also, when he received his larger specimens he had no adequate means of testing or further working them. He could only form " a tolerably correct judgment as to its general merits," and pass the material on to be made into instruments or tools, which were then subjected to " severe tests." Again and again, as one reads his papers, one is amazed to find how near he came to some of the major discoveries in the field of alloy steels, and one marvels anew at the keenness of his perception in such matters as corrosion tests, the influence of heat treatment, and so on. If only Faraday had had some of the advantages of a modern testing laboratory, or if only the true significance of his work on steel had been realised by others at that time, how different might have been the history of special steels !

Summary of Faraday's Results of 1820 and 1822

For our present purpose it will be convenient to abstract and collate information from both of Stodart and Faraday's papers (of 1820 and 1822) under the headings of the various elements alloyed with steel. Taking each of the elements nickel, silver, platinum, rhodium, iridium and osmium, palladium, titanium, chromium, and certain other metals in turn, the following interesting particulars are obtained :—

Nickel.—An alloy made from 10 of nickel with 80 of steel had a damask and was therefore unfit for mirrors ; it was also much more subject to rusting than an alloy of nickel and iron.

Silver.—After discovering that the proportion 1 silver to 160 steel resulted in buttons that were "uniformly steel and silver in fibres, the



FARADAY'S MICROSCOPE.

A. 6-in. tube with optical system.
B. Square brass pillar.
C. Universal joint.
D. Collapsible tripod.
E. Mount for the reflector.
F. Reflector.
H. Adjustable stage.
I. Brass bar carrying microscope tube.
K. Rectangular slot into which Bar I fits.
L. Gadgets for holding specimens on the stage H.
M. Tray for opaque specimens.
O. Eyepiece.
P. Diaphragm fitment with six apertures.
S. "Live boxes."
T. ,, ,,
V1. Objectives.
V2. ,,
V3. ,,

This illustration is reproduced through the kindness of Mr. A. Evelyn Barnard.

To face p. 117.]

silver being likewise given out in globules during solidifying," Faraday found that fibres could still be distinguished in specimens made from 1 part silver to 200, 300 and even 400 parts steel. When the proportion of silver was reduced, however, to 1 of silver with 500 of steel and properly fused, "a very perfect button was obtained; no silver appeared on its surface; when forged and dissected by an acid, no fibres were seen, although examined by a high magnifying power.* The specimen forged remarkably well, although very hard; it had in every respect the most favourable appearance. By a delicate test every part of the bar gave silver. This alloy is decidedly superior to the very best steel, and this excellence is unquestionably owing to combination with a minute portion of silver. It has been repeatedly made and always with equal success. Various cutting tools have been made from it of the best quality. This alloy is perhaps only inferior to that of steel with rhodium, and it may be procured at a small expense; the value of silver, where the proportion is so small, is not worth naming; it will probably be applied to many important purposes in the arts."

"From the facility of obtaining silver," says Faraday, "it is probable that its alloy with steel is the most valuable of those we have made. To enumerate its applications would be to name almost every edge-tool. It is also probable that it will prove valuable for making dies, especially when combined with the best Indian steel."

Trials "in the large way" at Sheffield with a mixture containing 1 of silver to 500 of steel resulted in an alloy which "had the most favourable appearance both as to surface and fracture; it was harder than the best cast steel, or even than the Indian wootz, with no disposition whatever to crack, either under the hammer, or in hardening. Some articles for various uses, have been made from this alloy; they prove to be of a very superior quality; its application will probably be extended not only to the manufacture of cutlery, but also to various descriptions of tools; the trifling addition of price cannot operate against its very general introduction. The silver alloy may be advantageously used for almost every purpose for which good steel is required."

Platinum.—Thanks to the generosity of Dr. Wollaston, Faraday was able to indulge in mixtures containing as much as 90 of platinum to 20 of steel. Perfect alloys were obtained in every proportion tried over a wide range, and the following conclusions are recorded: From 1 to 3 per cent. of platinum improves steel for edge instruments; probably about 1·5 per cent. of platinum forms the best possible alloy of these metals. Equal parts by weight form a beautiful alloy which takes a fine polish and does not tarnish; the colour is the finest imaginable for a mirror;

* It will be noticed that Faraday added to his other distinctions by practising an elementary form of the microscopic examination of the structure of steel. No doubt it was the macroscopic structure alone that he investigated, but in this, as in so many other directions, he worked on a line of investigation which was followed with far-reaching consequences by later workers. Plate XXVIII. shows the microscope actually used by Faraday. It now bears the inscription "Was Michael Faraday's about 1820–67. Given to James F. Barnard as a remembrance Mar. 1879." The author is indebted to Mr. A. Evelyn Barnard for permission to photograph this interesting instrument and reproduce the illustration in this book. The name of the maker, engraved on the tripod of the microscope, is "William Cary, London." This firm was well known in Faraday's time and did excellent work.

90 of platinum with 20 of steel also gives a perfect alloy with no disposition to tarnish; 10 of platinum to 80 of steel forms an excellent alloy, but one which is quite unfit for mirrors owing to a fine damask. This alloy, however, "after laying many months had not a spot of rust on its surface."

"From 1 to 80 per cent. of platinum was perfectly combined with steel, in buttons of from 500 to 2000 grains."

Equal weights of steel and platinum gave a button the highly crystalline surface of which rendered it unfit for a mirror.

Large-scale tests of steel with 1 per cent. of platinum led to the production of bars "remarkable for smoothness of surface and beauty of fracture." Though the alloy was not so hard as the 0·2 per cent. silver steel, "it had considerably more toughness: this property will render it valuable for every purpose where tenacity, as well as hardness, is required; neither will the expense of platinum exclude it from a pretty general application in the arts; its excellence will much more than repay extra cost."

Rhodium.—In the paper by Stodart and Faraday to the Royal Institution (1820) it is stated that "the alloys of steel with rhodium are likely to prove highly valuable. The scarcity of that metal must, however, operate against its introduction to any great extent." By the generosity of Dr. Wollaston, liberal supplies of rhodium were provided for the laboratory experiments and subsequently for the manufacture of rhodium steel "in the large way."

The proportions of rhodium used in the first series of investigations (1820 paper) were from 1 to 2 per cent., and the valuable properties of the rhodium alloys were found to be "hardness, with sufficient tenacity to prevent cracking either in forging or in hardening. This superior hardness is so remarkable, that in tempering a few cutting articles made from the alloy, they required to be heated full 30 deg. F. higher than the best wootz, wootz itself requiring to be heated full 40 deg. above the best English cast steel. Thermometrical degrees are named, that being the only accurate method of tempering steel."

In the second (1822) paper it is stated that rhodium combines with steel in every proportion and that from 1 to 50 per cent. of rhodium had been used successfully. Equal parts by weight of steel and rhodium gave a button which polished to "a surface of the most exquisite beauty: the colour of this specimen is the finest imaginable for a metallic mirror, nor does it tarnish by long exposure to the atmosphere: the sp. gr. of this compound is 9·76."

The alloys of steel with rhodium "are perhaps the most valuable of all; but these, however desirable, can never, owing to the scarcity of the metal, be brought into very general use."

Iridium and Osmium.—These metals are mentioned only in the second (Royal Society, 1822) paper by Stodart and Faraday and always together. From the wording of repeated references to them (and Faraday was meticulously careful in his writings) it appears that only ternary alloys of steel, iridium and osmium were investigated. The compound is said to be "of great value but . . . the scarcity and difficulty of procuring the metals will operate against its very general introduction."

It is certain that Faraday was deliberately investigating a ternary compound and realised its significance, for the following words occur in the Royal Society (1822) paper: "In the account now given of the different alloys, only one triple compound is noticed, namely, steel, iridium and osmium; but this part of the subject certainly merits further investigation, offering a wide and interesting field of research. Some attempts to form other combinations of this description proved encouraging, but we were prevented, at the time, by various other avocations, from bestowing on them that attention and labour they seemed so well to deserve. It is our intention to continue these experiments at every opportunity; but they are laborious, and require much time and patience."

Palladium.—This metal was used but sparingly by Faraday owing to its scarcity and cost, but 4 lb. of steel was alloyed with 1 per cent. of palladium in a single melt and "the compound is truly valuable more especially for making instruments that require perfect smoothness of edge."

Titanium.—Faraday made valiant attempts to alloy steel with titanium, but in this he was completely unsuccessful owing to the imperfections of his crucibles, which prevented him from attaining a temperature sufficiently high to reduce the oxide of titanium to the metallic state. After the utmost endeavour, the steel proved to contain no titanium.

Chromium.—M. Berthier, who first made the alloy of steel and chromium,* speaks very favourably of it. Stodart and Faraday made only two experiments. From 1600 grains of steel fused with 16 of pure chrome a button was obtained which "proved good and forged well; although hard, it showed no disposition to crack." On increasing the proportion of chromium, by using 48 grains of pure chrome to 1600 of steel, a considerably harder button was obtained; this, too, was as malleable as pure iron. Both of these alloys showed beautiful damasks, but "of the value of the chrome alloy for edge-tools we are not prepared to speak, not having made trial of its cutting powers."

From the circumstances of the case it would appear that Faraday's investigations of chromium steel were uncompleted when his steel researches were discontinued. If he had gone on he might well have discovered "stainless steel," for his papers show that he was quite prepared to try the effect of high proportions of alloying elements, he realised the importance of accuracy in heat treatment as mentioned on page 98. He had also embarked on a series of comparative corrosion tests, and advanced various hypotheses concerning the mechanism of corrosion.

Other Metals (*Copper, Tin, Gold*).—In the Royal Institution paper (1820) it is stated that "steel with 2 per cent. of *copper* forms an alloy; steel also alloys with *tin*; of the value of these we have doubts." Further trials were made to discover whether these and certain other combinations were at all likely to be interesting and useful, but no particular success appears to have been achieved and it is definitely stated in the Royal Society (1822) paper that "alloys of steel with *gold*, *tin*, *copper* and *chromium* we have not attempted in the large way." Trials were made in the laboratory with steel and gold in various

* *Annales de Chimie*, xvii. 55.

proportions, but it was found that though "gold forms a good alloy with steel . . . it certainly does not promise to be of the same value as the alloys of silver, platinum and rhodium"; and neither tin nor copper appeared at all to improve steel.

The more one reads the papers by Stodart and Faraday, the more one is impressed by the extent of the researches in question, and the more one feels that in a suitable environment Faraday might easily have discovered some of the steel alloys now used so extensively. The lack of suitable ferro-alloys, to which further reference is made later, was a great handicap, for without them Faraday had no convenient way of making a full range of alloys of gradually varying compositions. There was, as he rightly said, "an infinity of different metallic combinations to be made," and it was impossible for one man to try them all, specially in the course of only a few years' work and with the limited facilities then available.

The case of manganese steel is a striking example of the impossibility of achieving success except by the laborious process of trying every possible alloy. As the proportion of manganese in steel is increased above 2 or 3 per cent. the steel becomes increasingly brittle, until, with 4 to $5\frac{1}{2}$ per cent. of manganese, it can be powdered under the hammer. It might be argued that the higher the manganese, the worse should be the steel, but such assumption is entirely wrong, for, with more than 7 per cent. of manganese present, a new set of physical properties appears. Strength and ductility return, and with from 11 to 14 per cent. of manganese there is obtained that remarkable alloy, the Hadfield manganese steel, which when water quenched combines toughness and strength to such an extraordinary degree and becomes more resistant to deformation and wear the more severe the usage to which it is subjected.

Notwithstanding all our progress and the many investigators who have worked on the problems of alloy steels during the past fifty years, there is still an "infinity of different metallic combinations" awaiting investigation. It may well be found later that we of this generation have missed discoveries of the utmost importance by sheer chance, but the metallurgists of the future will surely not say that we failed in our researches on the alloys of steel. Still less ought we to accuse Faraday of failure because, working alone in a field which now employs hundreds of investigators, and armed with a mere fraction of the knowledge and resources we now enjoy, he did not produce any alloy which found enduring commercial application at that time. He did far more than that—he indicated to the world the whole field of alloy steel,

and he is entitled to the greatest possible credit as the precursor of our present era of special steels.

Specific Gravities of Faraday's Alloys

At the end of Stodart and Faraday's Royal Institution (1820) paper there is given the list of specific gravities of alloys reproduced in Table I. This is specially interesting in itself and it gains further importance from the fact that it proves that Faraday actually made alloys containing high percentages of platinum. Also, from the reasonably close agreement between the calculated and observed specific gravities of these materials it is clear that approximately the claimed proportion of platinum was actually present in the alloys. The later specimens found at the Science Museum and examined by the author confirm this to a considerable extent.

Table I.

Specific Gravities of Alloys, etc. (*Stodart and Faraday*, 1820)

Iron, unhammered	7·847
Wootz, unhammered (Bombay)	7·665
Wootz, tilted (Bombay)	7·6707
Wootz, in cake (Bengal)	7·730
Wootz, fused and hammered (Bengal)	7·787
Meteoric iron, hammered	7·965
Iron, and 3 per cent. nickel	7·804
Iron, and 10 per cent. nickel	7·849
Steel, and 10 per cent. platinum (mirror)	8·100
Steel, and 10 per cent. nickel (mirror)	7·684
Steel, and 1 per cent. gold, hammered	7·870
Steel, and 2 per cent. silver, hammered	7·808
Steel, and 1·5 per cent. platinum, hammered	7·732
Steel, and 1·5 per cent. rhodium, hammered	7·795
Steel, and 3 per cent. nickel, hammered	7·750
Platinum 50, and steel 50, unhammered *	9·862
Platinum 90 and steel 20, unhammered †	15·880
Platinum, hammered and rolled	21·250

The values given in this Table should be compared with those determined by the author, as given on p. 167.

It will be seen from the excerpts on the preceding pages that Faraday claimed to have produced steel and alloys which took a very high polish, withstood atmospheric corrosion, and carried better cutting edges than ordinary carbon steel. None of these claims can be substantiated to any pronounced degree by the

* The calculated mean specific gravity of this alloy is 11·2723, assuming the specific gravity of platinum and steel as expressed in this table.

† The calculated mean specific gravity of this alloy is 16·0766.

author's tests on the Royal Institution specimens of Faraday's steels, particulars of which are given on p. 189, but certain of the Science Museum specimens possess distinct claims to non-corrodibility, as shown on p. 226. In any case there is no reason to doubt that Faraday's remarks were quite correct as regards the specimens of which he was speaking, and as compared with the ordinary steels then available.

Not a single quantitative analysis is given by Faraday, for either the small specimens of alloys made in London or the larger ones produced in Sheffield, but the matter had by no means escaped his attention, as shown by the notes on p. 128.

Faraday's Letters to de la Rive

During his Continental tour with Davy in 1814, Faraday became acquainted with Professor Gaspard de la Rive, of the University of Geneva. A few years later, in 1819, he began to correspond with Professor G. de la Rive on scientific matters, following this later by a series of letters with his son, Professor Auguste de la Rive, F.R.S., extending over a period of thirty-eight years.

Two of Faraday's letters to Professor G. de la Rive are of special interest in connection with his researches on steel. Writing on April 20th, 1820, Faraday expressed his delight to the older man, already a famous professor, "that you had honoured me with any of your thoughts, and that you would permit me to correspond with you by letter."

Proceeding, Faraday said :—

"Mr Stodart and myself have lately been engaged in a series of experiments and trials on steel, with the hope of improving it, and I think we shall in some degree succeed.

"We are still very much engaged in the subject; but if you will give me leave I will, when they are more complete, which I expect will be shortly, give you a few notes on them."

This promise he kept to the full, for on June 26th, 1820, he wrote a long letter to Professor G. de la Rive giving what was substantially an abstract of the paper presented to the Royal Institution by Stodart and himself. This letter was published in the *Bibliothèque Universelle des Sciences*, also elsewhere, and attracted much attention; portions of special interest to us run as follows :—

Manufacture of Artificial Wootz.—"I must tell you the process by which we have prepared this alloy; we tried several methods, the following always succeeding:

"We melt iron in small fragments with charcoal powder. If the button which is produced is malleable it is necessary to break it and melt again with carbon. In this manner there is formed a carbure of iron intermediate between steel and plumbago (*plombagine*). It is

fusible, and when broken possesses a dark grey colour and is very crystalline. It is so friable that it can be reduced to powder in a mortar.

"We then mix this powder with pure alumina (*alumine*) and heat it strongly. A portion of the alumina is reduced by the carbon of the carbure and we thus obtain a compound of iron, aluminium and carbon. Then we mix ten per cent of this composition with English cast steel, submit the whole to fusion, and thus we obtain artificial wootz."

Alloys of Steel.—"You can easily understand that during the two years * that we have worked upon this subject, our experiments have furnished us with a large quantity of products of no use.

"I pass these by in silence in order to arrive at the alloys which have given us some quite happy results."

Rhodium and Steel.—"The best alloy steel we have made is perhaps that of rhodium and steel. It is Dr. Wollaston who has furnished us with the metal, so that from this there can be no doubt with regard to its purity or identity. One and a half per cent. of rhodium was combined with the steel. This alloy was very malleable, harder than ordinary steel, and made excellent instruments. In hardening these instruments it was necessary to heat them to at least 70° F. higher than necessary for the best cast steel; and this fact seems to indicate that the steel in question possesses greater hardness and density. Razors made with this alloy cut very admirably."

Silver and Steel.—"After the alloy of steel with rhodium came that with silver which presents many peculiar circumstances."

Faraday goes on to describe the rejection of the silver from mixtures of steel and silver on cooling and then says: "We continued to diminish the proportion of silver as long as we could observe its separated existence in the alloy, and when we arrived at one five-hundredth we found that the whole of the silver present remained in combination with the steel. This alloy was excellent, all the cutting instruments we made from it were of the best quality, and the metal could be worked without fissures occurring and with remarkable density and malleability."

Platinum and Steel.—"The alloy of steel and platinum does not appear to have any advantages so far as we have observed over the previous steel; however, it appears that platinum added to steel in the proportion of 1 to 3 per cent. might be of some utility; we are now actually occupied in following up this work. The powerful affinity with which platinum unites to metals does not show any exception when we combine it with iron and steel; they unite in all proportions; we have tried commencing with one part of platinum with 100, up to 90 platinum with 20 steel. We have every hope to obtain some happy results with these last compounds."

Nickel and Iron or Steel.—"We were led to try alloys of nickel and iron, or steel, by the popular idea that meteoric iron was not subject to

* From this it will be seen that Stodart and Faraday must have commenced some of their preliminary researches on steel and alloys at least as early as June, 1818. It is interesting to note that Faraday "passed by in silence" the "large quantity of products of no use." Evidently these must have been destroyed as no trace can be found of them. In one way this is unfortunate, as negative results, specially in alloy steels, are often of as great interest as the record of successes. It sometimes happens that results considered to be failures ultimately turn out to be more important than some of those which were at first considered successes.

rust. We have therefore made these alloys of iron and nickel, by varying the proportion of this latter metal, from three up to ten per cent, and we have been able to ascertain that these alloys are not as liable as iron to rusting, when they are exposed in a conservatory or in our laboratory. But nickel alloyed with steel was more oxidisable than pure steel; and this fact was not compensated by any other quality. We have therefore for the moment left this metal alone in our experiments although it may be possible that we shall take it up again later on."

It will be seen that this letter to Professor G. de la Rive covers substantially the same ground as the Royal Institution paper of 1820, but its different wording confirms, and in some instances quite usefully amplifies, the information presented in the paper. Also, the letter adds appreciably to our realisation of the extent and importance of Faraday's work, and to our conviction that this work represented an important advance on anything that had been done previously.

It was in concluding the above letter that Faraday wrote: "Pray pity us, that after two years' experiments we have got no further; but I am sure if you knew the labour of the experiments you would applaud us for our perseverance at least. We are still encouraged to go on, and I think the experience we have gained will shorten our future labours." Nearly a year later, on May 19th, 1821, he wrote another letter to Professor G. de la Rive, in which he said: "Mr. Stodart and myself are continuing our experiments on steel, which are very laborious." The results of this further work appear in the second paper by Stodart and Faraday presented to the Royal Society in 1822.

Faraday's Later Records

One of the tantalising aspects of the present investigation of the long and arduous work which Faraday devoted to the subject of alloys of steel is the absence of anything in the way of detailed laboratory notes in his own handwriting. The papers presented jointly with Stodart to the Royal Institution and the Royal Society are valuable in themselves, and indicative of the tremendous amount of labour devoted to this research, but they are necessarily formal records of what the authors considered facts sufficiently established to merit publication. As such, they represent only a small fraction of the whole series of observations which must have been made, and they contain nothing in any way comparable with the intimate record of procedure, failure and success which forms such a fascinating and valuable feature of Faraday's diary in later years. That famous series of notebooks, commenced in 1820, supplements his later papers in the most admirable manner

and throws a flood of light on Faraday's methods and researches. Unfortunately, not a line is available in the way of laboratory notes concerning the innumerable experiments on which the papers of 1820 and 1822 were based.

In fact, with the exception of the label on the box containing Faraday's seventy-nine specimens, the notes reproduced below are the only known surviving ones on steel in Faraday's own handwriting. The author has it on the authority of Mr. T. Martin, of the Royal Institution, for whose assistance on this point he is much indebted, that the following three items regarding steel are the only ones referred to in the diary between 1820 and 1832 :—

Steel Alloys

November 3rd, 1823

I. Platinum and steel welded.
II. do.
III. Twisted and forged steel to imitate Damascus.
IV. Pure iron fused.
V. Iron with 3 per cent. rhodium.
VI. Iron with 3 per cent. nickel.
VII. Steel 50, platinum 50.
VIII. Steel 20, platinum 80.
IX. Steel 50, rhodium 50.

Steel and Nickel

February 10th, 1824

565 grains of steel and 16 grains of nickel packed in a crucible together for fusion—February 11th.

Fused but being interrupted only imperfectly ; must fuse again.

Ultimately failed in furnace.

Steel and Nickel

June 28th, 1824

Packed up in a crucible for Mr. Christie.

1000 (parts) steel + 60 (parts) pure nickel.

Fusion July 4th (in) Crucible and (found) all right.

When opened fusion good but upper surface of the bottom very convex and again lower surface very cavernous.

When all liquid, must I think have been compact but on cooling perhaps gas has been evolved which has thrown it into that form.

It is probable that whilst Faraday devoted less of his time to the researches on steel after the death of Stodart on September 11th, 1823, from the entries in the diary it is evident that he continued the work until at any rate the end of June, 1824. It is hardly likely that the operations noted on November 3rd, 1823, February

10th, 1824, and June 28th, 1824, were the only work performed by Faraday on steel during this period, so that one is led to the conclusion that if further laboratory notes relating to steel were prepared, these were kept apart from the diary and, unfortunately, were not preserved. There is no doubt that the bulk of the work on steel alloys was done before Faraday began to keep his diary at all.

Faraday's Specimens at the Science Museum

As explained more fully in Chapter VII., specimens of some of the specially interesting alloys mentioned by Faraday in his diary notes of 1823—1824 were deposited in the Science Museum, South Kensington, by Mr. A. Evelyn Barnard, the nephew of Faraday's adopted daughter, Miss Jane Barnard. The author is much indebted to Colonel Sir Henry Lyons, Hon. D.Sc., F.R.S., the Director and Secretary, for permission to subject them to examination and analysis.

Full particulars of the results obtained from these specimens are given in Chapter VII., from which it will be seen that they supplement in a most interesting manner the seventy-nine specimens in the famous wooden box. They also help to confirm the interest of Faraday's research on "steel and alloys" and add considerably to our appreciation of the remarkable work he accomplished.

Faraday's Last Reference to His "Steel and Alloys"

After the year 1824 Faraday appears to have done nothing further in the way of research on "steel and alloys," and many years later, in 1863, when he was seventy-two years old and his memory had begun to fail, he could not even recall what had happened to the box of specimens which we have to-day. On March 17th, 1863, he wrote to his friend Dr. Percy, in response to an enquiry :—

"My Dear Percy,—It is very pleasant to see your neat handwriting again. I am quite tired in looking at my own unsteady, uncertain characters and sense. I wish I could have the further pleasure of helping you, but I have forgotten all about the paper on alloys, and cannot at all call to mind where any of the specimens are. I rather think they all went into Mr. Stodart's hands, and must be lost by this time, for I do not know how to trace them."

From this letter it may be inferred that most of Faraday's specimens passed into Stodart's hands, for the manufacture of experimental and other cutting instruments and the like. Probably some of these specimens remained in Stodart's workshops

till the latter were swept away by building improvements in the Strand. However this may be, it is quite certain that many of Faraday's specimens could not have gone to Stodart because some important work was done by Faraday nearly nine months after Stodart's death.

We may surely congratulate ourselves on Faraday's dereliction of memory in regard to the specimens. Without it, the precious specimens in the wooden box would almost certainly have been handed to Percy in 1863, and it is quite possible none of them would have survived until to-day. In 1863, Percy was no doubt collecting material for his famous book on *Metallurgy: Iron and Steel*, published in 1864, and he would doubtless have welcomed the opportunity of examining Faraday's specimens. It is, however, fortunate that this opportunity was denied him, for, great metallurgist though he was, Percy could not, nearly seventy years ago, have obtained a fraction of the information which has now been extracted from Faraday's specimens.

The record of Faraday's researches on alloys of steel as told by himself ends with his letter to Percy in 1863. In Chapter VII. the author passes on to the years 1930—1931, and explains how the opportunity of examining the surviving specimens arose, and how much the modern resources of science have revealed concerning these tiny pieces of steel, perhaps the most interesting of any in the world.

Before doing this, however, it will be interesting to discuss certain aspects of Faraday's work in relation to later conditions and developments, and to give such information as is available concerning the attempts to make practical use of his alloys more than a century ago.

Faraday and Steel Analysis

Attention has already been drawn, in Chapter II., to the comparatively primitive state of chemical knowledge at the time when Faraday was engaged in his researches on steel and alloys. Quantitative analyses could not be made with anything like the completeness and accuracy to which we are accustomed, and even chemical notation itself was still complicated by many old conventions. The curious sign ♂, depicting the lance and shield of Mars, the God of War, represented the metal iron, and Faraday stamped this sign on some of his specimens. Thus, referring to Table II., specimens C. 2-1; E. 1-1 to E. 1-8; and G. 1-1 are marked P♂, denoting an alloy of platinum with iron; and specimen C. 3-1 is marked R♂, denoting an alloy of rhodium with iron. The author's

analyses of these specimens, given in Table V., show that these symbols were used correctly by Faraday.

Although the notation then current seems strangely primitive to our eyes Faraday was, of course, quite familiar with it and used it correctly. Also, although chemical knowledge was then rudimentary as compared with that of to-day it must be remembered that Faraday was one of the leading chemists of his time and he made many important chemical discoveries during and immediately after the period in which he was engaged on steel researches. He was, in fact, at that time primarily a chemist, and he worked with marked success in the difficult field of organic as well as inorganic chemistry. As Sir William Pope, F.R.S., pointed out in his paper, "Faraday as a Chemist," read before the Royal Institution on June 12th, 1925, Faraday's book *Chemical Manipulation*, published in 1829, provides a fund of information concerning details of chemical experimentation of which the chemical student of to-day is entirely ignorant. The investigator of to-day is "now but little dependent on his own manipulative skill, and has become largely subservient to the ingenuity of the scientific instrument maker." These points deserve to be stressed because it is important to realise that Faraday was a great chemist and an experimental investigator of extraordinary genius. The general state of scientific knowledge was relatively primitive in his early days, but we may be sure that his researches on steel and alloys were conducted in no haphazard manner.

Accustomed as we are to complete analyses of steels it seems strange that a full analysis, as we now understand the term, is nowhere to be found in Faraday's papers. Faraday did not, however, overlook this matter, neither did he assume that what he placed in his crucible was necessarily to be found in the alloy he removed on the completion of his melting operations. The following extract * is remarkably interesting, and affords a striking example of the manner in which Faraday combined scientific procedure with practical common sense as regards avoiding laborious determinations—much more laborious then than now—where such would serve no useful purpose. Referring to the identification and examination of steel alloys, Faraday says :—

"A point of great importance in experiments of this kind was, to ascertain whether the products obtained were exactly such as we wished to produce. For this purpose, a part of each product was analysed, and in some cases the quantity ascertained ; but it was not considered necessary in every case to verify the quantity by analysis, because, in all

* From *On the Alloys of Steel*, by Stodart and Faraday, Royal Society, 1822.

the experiments made in the laboratory, the button produced after fusion was weighed, and if it fell short of the weight of both metals put into the crucible, it was rejected as imperfect, and put aside. When the button gave the weight, and on analysis gave proofs of containing the metal put in to form the alloy, and also on being forged into a bar and acted on by acids, presented a uniform surface, we considered the evidence of its composition as sufficiently satisfactory. The processes of analysis, though simple, we shall briefly state: the information may be desirable to others who may be engaged on similar experiments; and further may enable everyone to detect any attempt at imposition."

These instructions would clearly lead to the desired information with a maximum of certainty and a minimum of time and labour, which should surely be the aim of every scientific test designed for purposes of identification and checking, as distinct from the discovery of new properties or fresh information. The instructions given by Faraday for the individual analyses are equally concise and practical, as might be expected from so great a chemist.

Influence of Carbon

Faraday said in 1822 "it is not improbable that there may be other bodies besides charcoal capable of giving to iron the properties of steel." So far, carbon steel or alloys of steel also containing carbon retain their remarkable pre-eminence as regards capability of being hardened by heating and quenching in water. We have here, however, another instance of Faraday's high powers of perception, for the well-known metallurgist Sir W. C. Roberts-Austen, K.C.B., F.R.S., in his book *An Introduction to the Study of Metallurgy*, written at a much later date (1890), not only quoted Faraday's words as above, but went on to say :—

"The strange thing is that it is not known with any certainty whether, in the absence of carbon, other elements do play the part of the metalloid in enabling iron to be hardened by rapid cooling.

"Take the case of chromium, for instance; chromium carbon steel can, as is well known, be energetically hardened, but Busek * has asserted that the addition of chromium to iron in the absence of carbon does not enable the iron to be hardened by rapid cooling.

"Probably by employing the electrical method of heating adopted by Pepys a decision will be arrived at as to the hardening properties of elements other than carbon."

This reference to Pepys' classic experiment is specially interesting, in view of his association with Faraday (Chapter III.). By means of a very ingenious electrical apparatus,† Pepys heated an

* *Stahl und Eisen*, Vol. IX., 1889, p. 728.

† Full particulars of this experiment are given in a paper by J. G. Children, F.R.S., *Phil. Trans.*, 1815, p. 371.

iron wire in contact with diamond dust, all other materials being excluded; the iron was thus converted to "perfect blistered steel" where it had been in contact with the diamond. This experiment proved conclusively that the "steelification" of iron could be effected by the diamond alone, and the carbonaceous character of the latter was demonstrated beyond possibility of doubt. In the passage quoted above, Roberts-Austen suggests that the same method might be used to investigate the hardening properties of elements other than carbon. The author, however, doubts whether, in the absence of carbon, any other element can be found to equal the extraordinarily valuable properties of that element in alloys of iron.

Faraday and Heat Treatment

Evidence is available in Faraday's writings to show that he was fully cognisant of the great importance of the accurate heat treatment of steel. Thus, in dealing with the properties of rhodium steel, he states that it requires to be heated for tempering full 30° F. higher than the best wootz, which, in turn, must be heated full 40° F. higher than the best English cast steel. "Thermometric degrees are named," he continues, "that being the only accurate method of tempering steel." In this sentence there is not only an appreciation of the importance of a comparatively few degrees difference of temperature, but also an indication that the fact was not generally known at the time, otherwise it would hardly have been emphasised as it was.

In his book *Chemical Manipulation*, Faraday refers to the use of thermo-electric indications to determine the temperature of furnaces. It is true that at that time "the direct application to the determination of the higher temperatures had not been made practical in the hands of an ordinary observer," but it is clear that Faraday foresaw the importance and desirability of this being made possible.

Faraday and Rust and Corrosion Resisting Steels

In the introduction to the paper by Stodart and Faraday presented to the Royal Institution in 1820 on "Experiments on the Alloys of Steel made with a View to its Improvement," it is specifically stated that the secondary object of the investigations was to ascertain "whether any such alloys" (*i.e.*, any alloy found to be specially suitable for the making of cutting instruments) "would, under similar circumstances, prove less susceptible of oxidation." Thus, while it cannot be suggested that Faraday had

any idea of making "corrosion-resisting" steel in the modern sense of the term, there is no doubt that he hoped to produce alloys which would withstand rusting when exposed to ordinary atmospheric conditions. A considerable measure of success appears to have been obtained in this direction; thus, Faraday states that 10 of platinum to 80 of steel formed an excellent alloy, which after lying exposed for many months to the atmosphere indoors, had not a spot of rust on its surface. On the other hand, an alloy made from 10 of nickel to 80 of steel was found to be covered with rust after the same exposure under exactly similar circumstances, and Faraday calls special attention to the fact that an alloy of nickel with steel, that is containing higher carbon, is much more subject to oxidation than a similar alloy with low carbon iron as a base. In the 1822 paper, presented to the Royal Society, a more general statement to the same effect is made, viz.:—

"It is a curious fact, that when pure iron is substituted for steel, the alloys so formed are much less subject to oxidation. 3 per cent. of iridium and osmium, fused with some pure iron, gave a button, which, when forged and polished, was exposed, with many other pieces of iron, steel, and alloys, to a moist atmosphere: it was the last of all showing any rust. The colour of this compound was distinctly blue; it had the property of becoming harder when heated to redness and quenched in a cold fluid. On observing this steel-like character, we suspected the presence of carbon; none, however, was found, although carefully looked for. It is not improbable that there may be other bodies, besides charcoal, capable of giving the iron the properties of steel; and though we cannot agree with M. Boussingault,* when he would replace carbon in steel by silica or its base, we think his experiments very interesting on this point, which is worthy of further examination."

Faraday observed that different alloys were attacked by the same acid to different extents and he claimed that the relative vigour of the attack offered a means of distinguishing alloyed from plain steel, and even of forming a judgment as to the particular element present in the alloy. His observations as to the peculiar properties which some alloys exhibit when immersed in dilute acid, "not only mark and distinguish them from common steel, and from each other, but also give rise to some considerations on the state or particles of matter of different kinds when in intimate mixture or in combination, which may lead to clearer and more perfect ideas on this subject."

Faraday not only discussed the probable explanation of the phenomena which he observed, but also gave quantitative data concerning the relative corrodibility of various platinum steel alloys in different acids. Thus, he found that 0·25 per cent. of

* *Annales de Chimie*, XVI., 10.

platinum alloyed with steel increased the action of dilute sulphuric acid on the latter considerably; with 0·5 and 1·0 per cent. of platinum it was powerful; with 10 per cent. of platinum the acid acted, but not with much power; with 50 per cent. the action was not more than with steel alone; and an alloy of 90 platinum with 20 steel was not affected by the acid.

In Chapter VII. will be found the results of the author's tests with acids on some of Faraday's alloys. These provide excellent confirmation of Faraday's observations, both as regards the ready attack of sulphuric acid on the alloys with a low percentage, from 0·69 to 2·50 per cent., of platinum, and the contrary behaviour, that is difficulty of solution, of a high (48·6) percentage alloy. In the case of rhodium, however, while the alloy of similar high percentage (48·8) was even more difficult to dissolve, the low percentage alloys were not specially soluble, that is, as compared with ordinary steel.

Contemporary Use of Faraday's Steel Alloys

As already stated, some of Faraday's alloys were made "in the large way" by Sandersons, of Sheffield, and some were used by Green, Pickslay & Co. in the manufacture of fenders and razors. Unfortunately, there is no contemporary evidence available to show the total amounts of various alloys made in Sheffield, nor can any trace of the manufactured products be found, with the possible exception of two razors lent to the author by Mr. A. Evelyn Barnard, a nephew of Jane Barnard, who was Faraday's adopted daughter. Probably the total amount of alloy steel made at Sheffield from Faraday's mixtures, or in accordance with his instructions, was quite small, but there seems to be no doubt that stove fronts and fenders were made from his alloy of steel with silver and razors from his alloy of steel with rhodium.

By the courtesy of the Royal Institution, the author is able to reproduce certain letters written to Faraday by the firm of Green, Pickslay & Co., Sheffield. These are of great interest as showing the enterprise of this Sheffield firm, which was, to judge by the letters, rewarded by a certain measure of practical success. It will be seen that Mr. Charles Pickslay continued his active interest in the matter for a period of at least two and a half years, one letter being dated April 14th, 1824, and another November 16th, 1826. The third letter is undated, but, from its tenor, appears to have been of intermediate date. Evidently Faraday must have corresponded with the firm, but no trace of his letters can be found.

It is specially interesting to note that Mr. Pickslay's last-dated

letter was written nearly two and a half years after the latest entry in Faraday's diary concerning steel and alloys.

The first letter, from C. Pickslay to Stodart and Faraday, read as follows :—

"MESSRS. STODART & FARADAY.

"Gent[n],—I sometime since read with considerable interest your essay on the alloys of Steel & being convinced that some of them might be introduced with great advantage into our own manufactory, for the various descriptions of Cutlery as well as for the fronts of Stoves and Fenders I determined to make an experiment in the large way with Steel & Silver and if the price of the alloys do not prohibit them with Platina and Rhodium, but as the success of the experiment depends upon 'a faithful and diligent attention on the part of the operator' which I could not insure unless I superintend it in all its processes I deferred it until we had erected some new workshops we were building, they are now nearly complete & we shall soon be able to have the Steel made & the article finished on our own premises. The whole process of Casting, Forging, Hardening, & Grinding will be carried on under my own inspection or of one of my partners.

"Will you have the goodness to inform me if any further instructions are necessary than those published in the Rep[y] of Arts for Jan[y] 1823 and where the alloys are to be obtained on the best terms & the price. In return we shall have great pleasure in presenting you with fenders made of the improved Steel if it succeeds to our expectation.

"I am, Gent[n]
"Your obd. Hble. Ser[t.]
"C. PICKSLAY.

"SHEFFIELD, *April* 14, 1824."

This latter was evidently a preliminary enquiry such as might be sent by an enterprising firm contemplating the taking up of a new line of manufacture. The reference to the new workshops under construction; the capability of making steel and finishing articles on the firm's own premises; and the personal supervision mentioned by Mr. C. Pickslay are points of special interest.

An undated memorandum, probably coming next in order of date, is as follows :—

"From : GREEN, PICKSLAY & CO.
"To : MR. FARADAY.

"Green, Pickslay & Co. have great pleasure in informing Mr. Ferrady that they have made a number of experiments with the alloys, recommended by him, and find the Steel greatly improved by them; they send a specimen alloyed with silver, Iridium, and Rhodium, which they consider the best they have produced, these alloys with some valuable practical hints, have been furnished by Mr. Johnson, No. 79 Hatton Garden *; the Report of the Forgers is that the steel works better under

* The business in precious metals is still carried on at this address by Messrs. Johnson, Matthey & Co., Ltd., and on a very extensive scale.

the Hammer than any they have before used, and likewise hardens in a much superior manner.

" Green, Pickslay & Co. beg Mr. Ferrady's acceptation of a pair of Rasors made from this Steel. They will have great pleasure in sending other Specimens of Cutlery &c as they continue their experiments.

In pencil not the same handwriting } " Ironmongers,
" High Street,
" Sheffield."

This communication pays high tribute to the quality of " Mr. Ferrady's " alloys, and may be taken as genuine, for the forgers were not likely to praise the working of the steel and its hardening properties unless they found the material really superior in these respects. The reference to Mr. Johnson, of Hatton Garden, is interesting; presumably he supplied the silver, iridium and rhodium for alloying and not the actual alloys themselves.

The third letter reads as follows :—

" Sheffield,
" *Nov.* 16, 1826.

" Sir,—We continue our experiments with the alloys much to our own satisfaction, but greatly to the annoyance of some of our Neighbours, who wish to avail themselves of your important discoveries, but have not the spirit to incur the necessary expense.

" I enclose you a Newspaper, in which you will observe, an attack upon our Peruvian Steel. We must however admit the writer has cause (from the conduct of some other manufacturers) to draw the inference he has done.

" I send you a rasor, marked ' Silver Steel,' it is made of the commonest Steel that can be produced, the Person who forged it informs me, he makes a great quantity, of the same quality all marked ' Silver Steel.' We therefore deem it prudent to keep the alloys we use secret, for should we publish them, the same Persons who mark ' Silver Steel ' on such spurious articles as the blade sent, would not hesitate to assert that they used the same alloys as we did, and thus bring it into disrepute.

" At the same time we shall be happy to give you confidentially any information you may wish, but for the reason stated, you will agree with us it is not desirable to make it public.

" We beg your acceptance of a pair of Peruvian steel scissors, that you may judge what Polish it will receive. The Grinders were very much prejudiced against it, but now admit it bears a finer colour, than any other that comes into their hands.

" I remain, Sir,
" Most respectfully,
" Yours obt. hble. Servt.

" Chas. Pickslay.

" M. Faraday Esqre
" Royal Institution."

This document indicates that the firm of Green, Pickslay & Co. had devoted a great amount of work to the subject of steel alloys and incidentally reveals troubles of a nature still not unknown.

As regards the firm of Green, Pickslay & Co. itself this concern seems to have been one of considerable importance in its day. Some idea of its activities may be gathered from the following notes, based on early directories of Sheffield, *Peeps into the Past*, by Thomas Asline Ward (1781—1871), Master Cutler of Sheffield in 1816, and *Reminiscences of Old Sheffield*, by R. E. Leader.

The firm was mentioned in directories as Green and Pickslay in 1821, Green, Pickslay and Appleby in 1825, Pickslay, Appleby and Bertram in 1828, and Charles Pickslay & Co. in 1833 and 1841, the latter being the last year in which the firm is mentioned in a directory.

Mr. Green was "fond of field sports and had the entrée of very good houses, but he had to give his great friends long credit and was not the man to ask for payment, so that the inevitable end resulted." Mr. Green came to poverty and the business was carried on by Pickslay, Appleby and Bertram for a time. Later Charles Pickslay's name appears alone. From these facts, and the fact that Charles Pickslay signed the letters reproduced above, one may infer that he was the technical and working partner and that he was a man of enterprise and steady application.

The firm is described as "perhaps the first and most extensive iron-mongers in Yorkshire, and noted for a peculiarly excellent cast steel which they called 'Peruvian.'" Throughout the period 1821–1841 they appear to have been high-class cutlers, and they also had their own foundry and made stove grates, fenders, balustrades, and so forth.

From 1833, Charles Pickslay & Co. confined themselves to the manufacturing part of their business, and one infers from Mr. Pickslay's letters to Faraday that he was always specially interested in this side of the business. Evidently he did not succumb to the credit trading which ended so disastrously for Mr. Green.

Charles Pickslay died at his residence, Endcliffe Cottage, in 1852, aged seventy-one years.

The correspondence between Green, Pickslay & Co. and Faraday seems to show an honest belief on the part of that firm in the merits of the silver, iridium and rhodium alloys of steel. It not only shows an enterprising spirit on the part of a Sheffield firm—for apparently the initiative was taken by them after reading an account of Faraday's work—but also constitutes a definite link in the chain of development. These letters are, in fact, first-hand evidence of a well-sustained attempt to make practical use of Faraday's discoveries, and they must be some of the first, if not the first, letters bearing on the commercial development of alloy steel. They reveal the fact that a firm, celebrated in those days, thought highly of Faraday's work and found his alloys of such superiority, compared with other materials then available, that they were

quite pleased to continue their experiments and practical production of them for at least two and a half years. During this period the firm went to considerable expense in the trials and appears to have been well satisfied by the results.

What happened later must remain a matter for speculation. In his letter of November 16th, 1826, Charles Pickslay offers further information to Faraday, but asks him not to make it public. If Faraday took advantage of this offer we may be sure he would observe the condition attached and thus, in all probability, the experience gained by Pickslay was lost when his firm ceased to exist, about the year 1842.

Faraday presented razors made from his alloys to friends at various dates. Probably these razors were made by Green, Pickslay & Co. (or Chas. Pickslay & Co.). By the courtesy of Mr. A. Evelyn Barnard, the author has been permitted to test two razors which formerly belonged to Faraday, one bearing the wootz sign and the other marked " Silver steel." Full particulars of the tests on these razors are given in Chapter VII.

CHAPTER VII

MODERN INVESTIGATION OF FARADAY'S STEEL AND ALLOYS

The Author's Research

As explained in the course of this chapter, the author has had the privilege of subjecting to full and complete examination seventy-nine specimens of Faraday's "steel and alloys," which were placed by Faraday himself in a wooden box well over a century ago. The author has also had the privilege of subjecting to complete examination a further group of specimens, namely, some of those mentioned by Faraday in his diary. Hitherto, none of these specimens in either group has been submitted to anything in the way of quantitative determination of composition and properties. Many of them had been forged into small bars, either by Faraday or by someone acting for him, and a few had been polished, but that was all. Faraday nowhere gives a full analysis of any of his specimens, though he checked their composition by the method explained on p. 128, Chapter VI. As regards the methods of testing employed by the author other than chemical analysis, namely, metallographic, spectroscopic, hardness tests, electrical and magnetic tests, these were not known at the time of Faraday's research on steel and alloys, and they have certainly never before been applied to his specimens. The author's investigation and examination are therefore unique, that is, specimens of alloy steels made more than a century ago have been subjected to the fullest possible examination by the resources of a modern research laboratory. Much interesting information has been obtained, and as the present research proceeded it became increasingly evident that it was of considerable importance, and that Faraday's work on his steel and alloys undoubtedly constituted the first true and scientific research on the important subject of the alloys of iron with other elements.

In addition to the chemical and physical examination of the seventy-nine specimens, it has been possible to make miniature knives and a razor from certain of Faraday's alloys, and tests have been made on a few specimens deposited in the Science Museum by Mr. A. Evelyn Barnard, these specimens being additional to

the seventy-nine in the historic wooden box. Also, two of Faraday's razors, kindly lent to the author by Mr. A. Evelyn Barnard, have been subjected to examination and comparison with two other razors made by Pepys and Stodart respectively.

The author's research thus falls under the headings :—

(1) *Main Research on Faraday's Specimens.*—Full examination and testing of the seventy-nine specimens in Faraday's wooden box. The total weight of these specimens was only 7 lb. 14 oz., and only about 1 lb. 3¾ oz. has been used up in the course of analysis and testing.

(2) Manufacture of a razor and miniature knives from Faraday's material.

(3) *Researches on Further Specimens of Faraday's Alloys.*—Full examination and testing of specimens of Faraday's steel and alloys mentioned in Faraday's Diary, November 3rd, 1823.

(4) Examination of historic razors, namely, one by Pepys, one by Stodart, and two belonging to Faraday, one of these being of wootz, the other of silver steel.

The examination and testing of the specimens of these steels and alloys and of the historic razors have been made in the Hadfield Research Laboratories, Sheffield. A full account of the results obtained is given later in this chapter and, as shown by Tables IV. and XVII., the work has involved many hundreds of analyses and tests, all of which have been conducted on a remarkably small amount of material, thus the specimens themselves still remain comparatively intact.

Thanks to the superior methods of testing now available, Faraday's results are seen in a very different light from that in which they have hitherto been regarded. The author has on many occasions in the past drawn attention to the fact that Faraday was interested in and experimented on alloy steels, but he freely confesses that he had not appreciated the full importance and significance of this work until the opportunity arose of examining the specimens which Faraday prepared.

Circumstances of the Main Present Research

In August, 1930, the author saw a few specimens of Faraday's steel and alloys in the Science Museum, South Kensington, where they had been placed on exhibition, under the care of Colonel Sir Henry Lyons, F.R.S., during the reconstruction of the Royal Institution building. As an exhibition of Faraday's apparatus, instruments and other material was to be held in the Royal Albert Hall, London, during the Faraday Centenary Celebrations,

under the management of a special committee, with Colonel Vignoles as chairman, the author suggested that it would be interesting and appropriate to have the specimens of Faraday's steel submitted to complete examination and analysis. The author further discussed this suggestion with Sir William Bragg, F.R.S., Fullerian Professor of Chemistry, Director of the Laboratory and Superintendent of the House, who now occupies the high position so long held by Faraday himself. It was recognised that Faraday's researches on "steel and alloys" and his own account thereof would acquire a new and greater interest if some of his actual specimens could be completely examined by the latest methods. It was therefore with much pleasure and satisfaction that the author received on November 3rd, 1930, an official letter from the Royal Institution stating that the Managers saw no objection to the author's proposal and granted the necessary permission for the examination and testing of these specimens.

This permission was granted not only regarding the few specimens on loan from the Royal Institution to the Science Museum, but also as regards the whole of the contents of the wooden box in which Faraday placed this set of specimens, probably in the year 1822. This box is shown in Plate I., and more is said later concerning it and its contents. For the moment, it is sufficient to say that the box was found to contain a remarkable collection of alloy steels containing low percentages of the added elements, which undoubtedly represent some—but only a part—of the fruits of the researches described in Stodart and Faraday's papers of 1820 and 1822. These were the first true and scientific researches on the important subject of alloys of iron and steel with other elements, and they represent the first important research work conducted by Faraday, his earlier work being in the nature of comparatively small investigations, as shown by the Bibliography.

Examination of the contents of the historic wooden box revealed no trace of certain high-alloy specimens mentioned by Faraday in his papers and in his diary. The absence of these was specially disappointing because it was evident that such an alloy as steel containing 50 per cent. rhodium, to mention only one example, might be expected to have unusual properties, curious and interesting if proving not to be of any practical value.

On the completion of the author's investigation of the seventy-nine specimens in the wooden box, when it became certain that none of these was a high-alloy specimen, Mr. A. Evelyn Barnard, nephew of Miss Jane Barnard, the adopted daughter of Faraday, drew the author's attention to certain specimens which he had

deposited in the Science Museum, South Kensington. These it should be clearly understood are quite distinct from the few specimens previously mentioned as being on loan from the Royal Institution. The specimens presented by Mr. Barnard were found to be wrapped in paper bearing faded endorsements, apparently in Faraday's handwriting, which made it clear that these were actually some of the specimens produced by the experiments mentioned in Faraday's diary under the date November 3rd, 1823. By kind permission of Mr. Barnard and the Director of the Science Museum, Colonel Sir Henry Lyons, F.R.S., the author has been allowed to subject these specimens also to full examination. They do not comprise all the specimens mentioned in the diary records, but they include a sufficient number to leave no doubt that they are indeed from this group. The low-alloy specimens in the wooden box are equally certainly representative of the earlier researches.

The Wooden Box and Its Contents

No record has been found of the date when the famous wooden box was made and filled with the specimens of steel and alloys. It is quite possible that this was done in order that a set of specimens might be exhibited to the Royal Society when Stodart and Faraday presented their paper " On the Alloys of Steel " in 1822. There can be no doubt that the specimens were placed in the box by Faraday himself for it bears labels in his handwriting :—

" Faraday "
" Steel and Alloys "

The box, which is made of deal, measures about $9 \times 5\frac{1}{2} \times 5\frac{1}{4}$ inches, and contained seventy-nine specimens of steel and alloys, of which only thirteen weighed 100 gm. ($3\frac{1}{2}$ oz.) or over, the heaviest 140·1 gm. (5 oz.), while the remaining sixty-six averaged only 31 gm. (1·1 oz.). The total weight of metal was only 7 lb. 14 oz.

The appearance of the box and its contents is shown by Plates I. and II. The dimensions, weights and other particulars of the individual specimens are given in Table II., and a " balance sheet " showing the use made of the specimens for purposes of testing is given in Table III. A full account of the analyses of the specimens, and of the mechanical, physical, metallographic and other examinations to which they were subjected, is given in the following pages.

From his own experience in the discovery and invention of manganese steel, silicon steel and other special alloys, including

investigation of their properties from a scientific standpoint, the development of their manufacture on a large scale, and their application to engineering and other purposes, the author has always had great sympathy with the difficulties of pioneers and special interest in the history of steel. For these reasons and because of the great amount of interesting information derived from the study of Faraday's specimens now placed on record for general use, the author wishes to express his best thanks to the Chairman, Sir Robert Robertson, F.R.S., and the Board of Managers of the Royal Institution for their generous permission in placing these Faraday specimens of "Steel and Alloys" at the author's disposal to carry out the present research; he also begs to thank Sir William Bragg, F.R.S., Director of the Laboratory, Superintendent of the House and Fullerian Professor, for the very kind help he has rendered and the interest shown in this research; also to the Royal Institution staff, including Mr. Thomas Martin, M.Sc., General Secretary; Mr. W. J. Green, B.Sc., Assistant in the Laboratory; and Mr. Ralph Cory, the Librarian, for their valuable assistance.

An account of the author's extensive research on the specimens in the famous wooden box, including their examination and tests, was published for the first time in a paper entitled "A Research on Faraday's 'Steel and Alloys,'" presented to the Royal Society and appearing in *Phil. Trans.* A. Vol. 230, September, 1931.

Acknowledgment is due to the Council of the Royal Society for their permission to embody in the present work information from that paper concerning these tests, together with various Tables and Figures, also to the help rendered to him by the Assistant Secretary, Mr. F. A. Towle; Mr. R. Winckworth, M.A., the Librarian, and his assistant, Mr. H. W. Robinson, in getting together various literature containing the historical references required by the author, of which many have been found of considerable service.

The author returns his best thanks for the willing assistance afforded by Mr. W. J. Dawson, Metallurgical Director of Messrs. Hadfields, and the staff of their Research Laboratory, including Mr. T. G. Elliot, F.I.C., and his assistants, Messrs. G. B. Willey, F.I.C., A.R.S.M., West and Arnold, with regard to the chemical and metallographic examinations; Mr. S. A. Main, B.Sc., F. Inst.P., who as regards the mechanical, physical and many other tests was assisted by Mr. T. H. Burnham, B.Sc.; Messrs. Todd, Spiller and Stevenson; the author is further indebted to the patient and careful work displayed by Mr. T. Melling, assistant works manager at the

Hecla Works of Messrs. Hadfields, for carrying out the numerous drillings for analysis often of delicate nature including difficult specimens such as razors, forging and other operations; also to Mr. H. Hallatt and his staff for much clerical work.

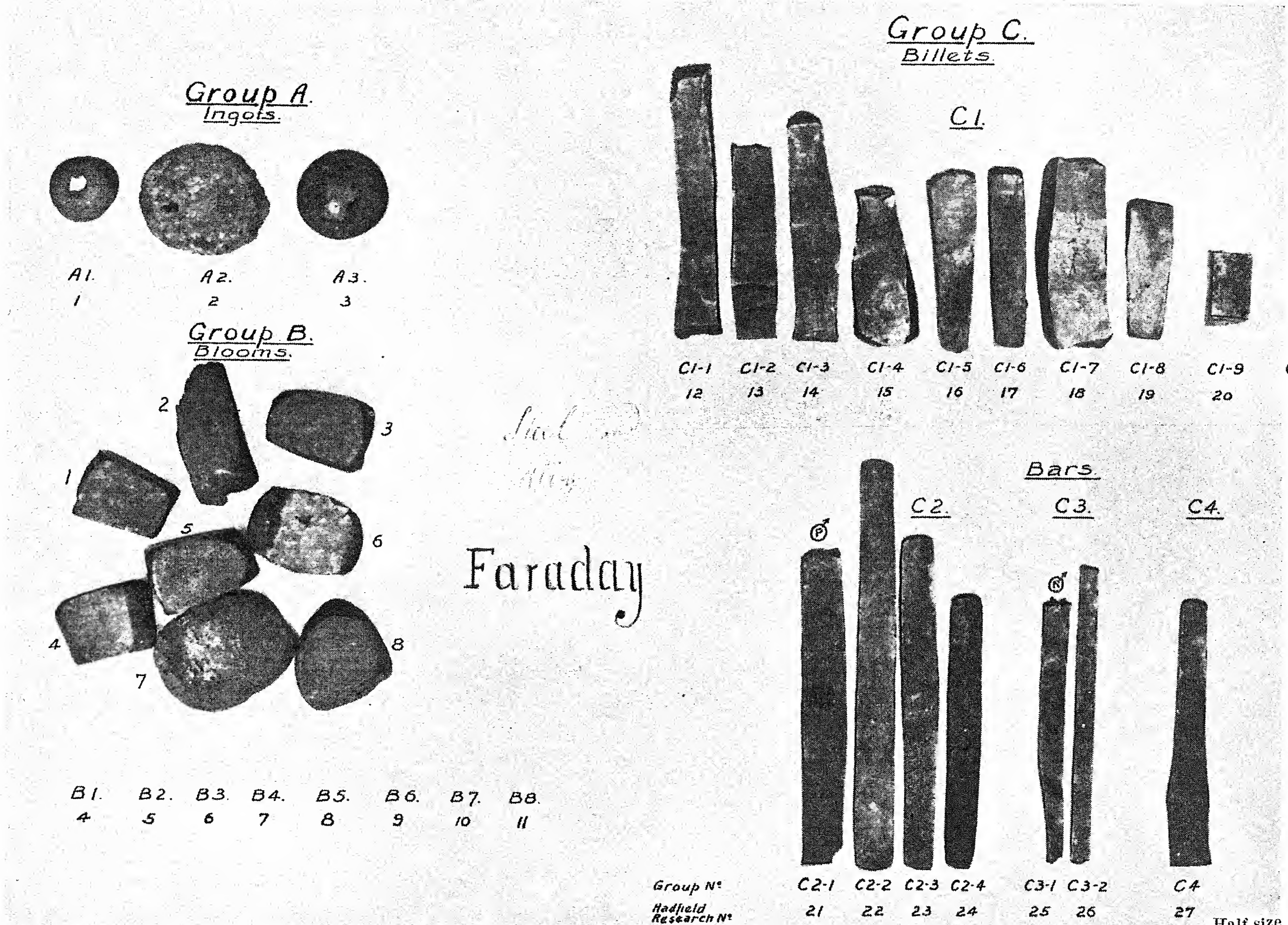
With so many specimens requiring full and careful examination, the work carried out has been long and arduous. Nevertheless, the help afforded has been most cheerfully rendered. To one and all the author expresses most cordial thanks.

Scope and Difficulties of the Author's Research

On taking charge of the wooden box containing the earlier collection of Faraday's specimens of steel and alloys, the author at once proceeded to sort them out. The manner in which they finally came together in sets was somewhat remarkable, showing the careful planning of the research by Faraday. This is clearly indicated by the classification arrived at in Table II. and Plates XXIX. and XXX. Beyond a few special marks on some of the specimens, there was, however, nothing to indicate their actual nature, probable composition, how made or treated, and so on. Information provided in Stodart and Faraday's papers of 1820 and 1822 afforded some useful clues but, in the main, the author had to start work with but little definite information to guide him, and subject to the difficulty that only an absolute minimum amount of material might be used for the purposes of the various tests. The intensive search for contemporary information regarding Faraday's research led to further investigations concerning the part played by those with whom Faraday came in contact. The scope of the work thus grew rapidly, entailing a vast amount of labour for all concerned—a labour of love, but a labour none the less.

It is not possible to determine the composition and qualities or the full nature of a specimen of steel merely by observing its fracture, by metallographic examination, or by spectroscopy, useful as each of these is in its own place; full chemical analysis is also essential. The spectroscopic method proved of service in the preliminary examination of some of the specimens, but complete chemical analysis, mechanical and other tests were required to arrive at a full knowledge of the steels and alloys. It was desired that not more than about 20 per cent. of each specimen should be used for analysis and other testing purposes, but the author had permission to use more if essential, provided that a material weight of each should remain. As will be seen from the "balance sheet," Table III., it was found possible to complete

To face Plate XXX, p. 142.]



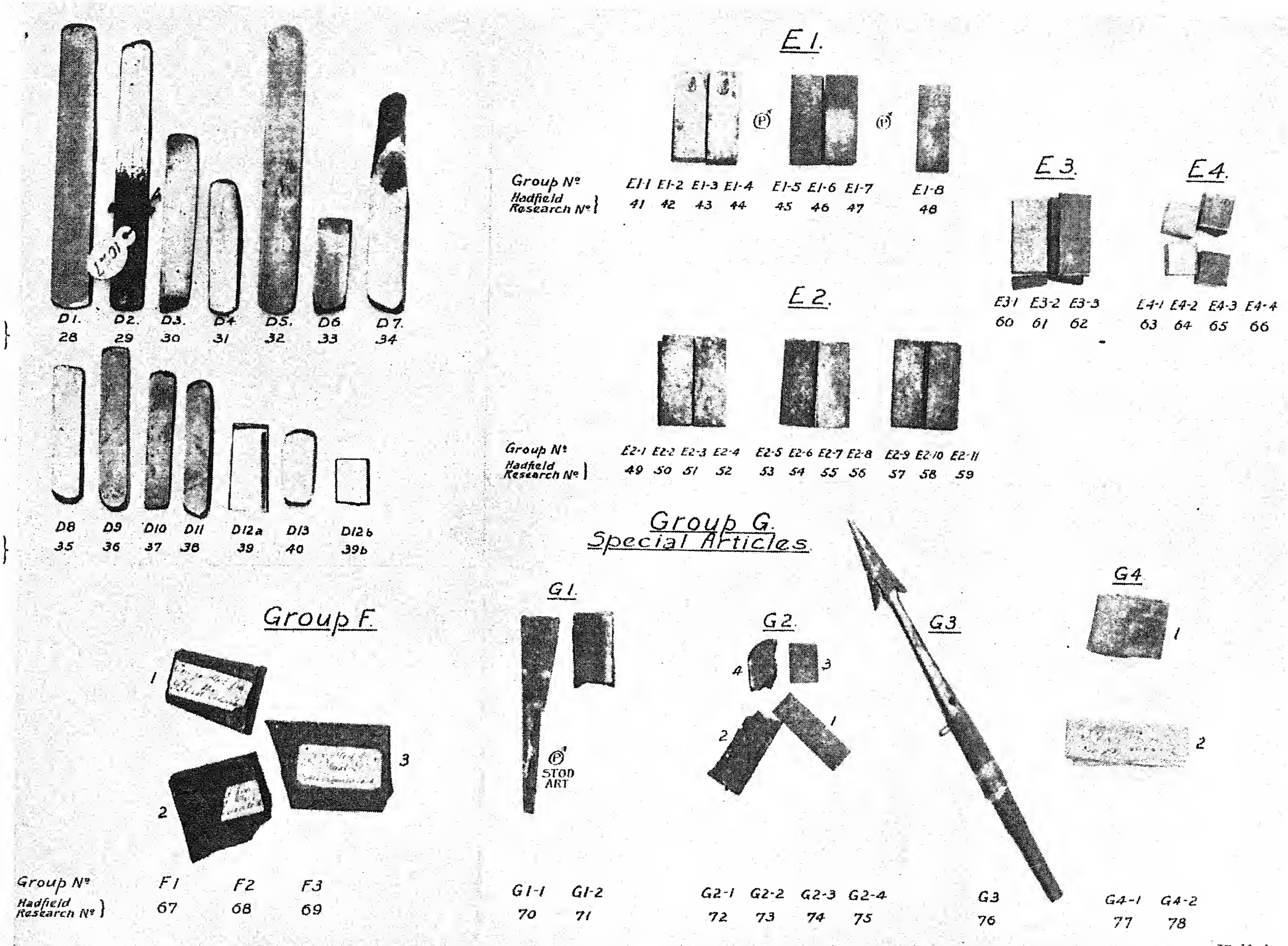
Group No. Hadfield Research No. (left, upper row; right, upper row; left, lower row)

Half size

GROUP ARRANGEMENT OF THE SEVENTY-NINE STEEL SPECIMENS FROM THE BOX SHOWN IN PLATE I.
(SECTION 1).
The further nine specimens of "steel and alloys" discovered later and prepared by Faraday in 1823 are shown in Plate L.

Group No.
Hadfield
Research No.

Group No.
Hadfield
Research No.



Half size

GROUP ARRANGEMENT OF THE SEVENTY-NINE SPECIMENS FROM THE BOX SHOWN IN PLATE I.
(SECTION 2.)

The further nine specimens of "steel and alloys" discovered later and prepared by Faraday in 1823 are shown in Plate L.

[*To face Plate XXIX.*

Table II

General Particulars of the Specimens Arranged in Groups

1	2	3	4	5	6	7	8	9	10
					Size in Centimetres.				
Hadfield Research Number.	Group Mark.	Faraday's own Mark.	Type of Specimen whether cast or forged.	Description of Specimen.	Length.	Breadth.	Thickness.	Weight. Grams.	Nature of Fracture.
GROUP A. (Ingots.)									
1	A-1		Ingot	Black	1·75	2·25	2·25	43	
2	A-2				1·75	4·50	4·00	105	
3	A-3				2·75	3·00	3·00	130	
GROUP B. (Blooms.)									
4	B-1		Bloom	Black	3·00	2·70	2·40	121	Medium crystalline.
5	B-2				5·00	2·25	2·25	118	
6	B-3				3·50	2·50	2·25	116	Fine crystalline.
7	B-4				2·40	3·50	2·50	121	Very fine grey crystalline.
8	B-5				3·50	2·60	2·40	130	
9	B-6				1·50	4·00	2·90	102	Medium crystalline.
10	B-7				1·25	5·00	4·00	118	Coarse bright crystalline.
11	B-8				3·50	3·00	2·50	140	Very fine grey crystalline.
GROUP C. (Billets.)									
12	C1-1		Rough Billets	Black	9·75	1·30	1·00	100	Very fine grey granular.
13	C1-2				7·00	1·50	0·80	60	Very fine grey.
14	C1-3				8·25	1·50	1·25	99	
15	C1-4				1·25	2·00	1·25	77	
16	C1-5				6·50	1·30	1·30	83	
17	C1-6				6·50	1·30	1·00	59	
18	C1-7				7·00	2·25	1·00	126	
19	Cl-8				5·00	1·50	1·25	69	Very fine crystalline.
20	Cl-9				2·50	1·30	1·30	35	Fine crystalline.
21	C2-1	P♂ 2	Forgings	Black	11·00	1·50	0·80	98	
22	C2-2				14·50	1·30	0·40	64	Very fine light grey.
23	C2-3				11·75	1·20	0·60	63	
24	C2·4				9·50	1·20	0·70	55	
25	C3-1	R♂			9·00	0·80	0·60	33	
26	C3-2				10·50	0·70	0·30	17	
27	C-4	2			9·30	1·00	0·70	41	
GROUP D. (Bars.)									
28	D-1		Bars	Polished				79	Close light grey granular.
29	D-2				9·50	1·10	0·80	62	Close light grey granular.
30	D-3				6·25	1·00	1·00	49	
31	D-4				4·75	1·00	0·80	29	
32	D-5				10·00	1·30	0·60	66	Very fine grey crystalline.
33	D-6				3·50	1·10	0·90	27	
34	D-7				7·50	1·50	1·25	98	
35	D-8				4·75	0·90	0·90	29	
36	D-9				5·75	1·10	0·90	44	
37	D-10				5·00	0·90	0·90	28	
38	D-11				5·00	1·00	0·90	34	
39	D-12A				3·00	1·30	0·60	17	
39B	D-12B				1·40	1·10	0·45	6·07	
40	D-13				2·50	1·10	0·80	15	

SPECIMENS A–1, A–2 AND A–3, ALSO SPECIMEN B–7 ARE OF CAST MATERIAL.

The marks P and R were no doubt intended to indicate the addition of Platinum or Rhodium to the alloys on which they appear, as was afterwards found to be the case; ♂ is the Zodiac sign for Mars, used also symbolically for the metal iron.

TABLE II (*continued*)

General Particulars of the Specimens Arranged in Groups

1	2	3	4	5	6	7	8	9	10
					Size in Centimetres.				
Hadfield Research Number.	Group Mark.	Faraday's own Mark.	Type of Specimen whether cast or forged.	Description of Specimen.	Length.	Breadth.	Thickness.	Weight. Grams.	Nature of Fracture.
GROUP E.									
41	E1-1	♂P 3 nicks			3·10	1·10	0·60	17	
42	E1-2	♂P 3 nicks			3·10	1·10	0·60	17	
43	E1-3	♂P 3 nicks			3·10	1·10	0·60	16	
44	E1-4	♂P 3 nicks	Small flat pieces	Black	3·10	1·10	0·60	16	
45	E1-5	♂P 2 nicks			3·10	1·10	0·60	16	
46	E1-6	♂P 2 nicks			3·10	1·10	0·60	17	
47	E1-7	♂P 2 nicks			3·10	1·10	0·60	17	
48	E1-8	♂P 1 nick			3·10	1·10	0·60	15	
49	E2·1	3 nicks			3·20	1·10	0·60	17	
50	E2·2	3 ,,			3·10	1·10	0·50	15	
51	E2·3	3 ,,			3·10	1·10	0·60	16	
52	E2·4	3 ,,			3·00	1·10	0·60	15	
53	E2·5	2 ,,	Small pieces with nicks.		3·00	1·10	0·60	16	
54	E2·6	2 ,,		Black	3·00	1·10	0·50	15	
55	E2·7	2 ,,			3·10	1·10	0·50	14	
56	E2·8	2 ,,			3·10	1·10	0·60	16	
57	E2·9	1 nick			3·10	1·10	0·50	14	
58	E2·10	1 ,,			3·10	1·10	0·40	13	Fibrous and fine crystalline.
59	E2·11	1 ,,			3·00	1·10	0·50	14	
60	E3·1		Pieces flat bar.	Black	3·20	1·20	0·60	19	Fine grey (old fracture).
61	E3·2				3·00	1·20	0·50	15	,, ,,
62	E3·3				3·00	1·20	0·50	15	,, ,,
63	E4·1				1·10	1·10	1·10	10	
64	E4·2		Cubes.	Black	1·10	1·10	1·10	10	
65	E4·3				1·00	1·10	1·10	10	
66	E4·4				1·20	1·10	1·10	12	
GROUP F.									
67	F-1	Crude steel from the blast furnace annealed.	Flat specimens	Black	2·30	3·10	1·20	59	Fine grey (old fracture).
68	F-2				3·00	3·10	1·20	73	Very fine grey crystalline.
69	F-3				3·70	3·10	1·20	103	Very fine grey crystalline.
GROUP G.									
70	G1-1	♂P Stodart.	Knife blades.	Black	7·00	1·50/0·50	0·20	6	
71	G1-2		Knife blades.	Partly polished.	2·60	1·50	0·60	12	Close light grey crystalline.
72	G2-1				3·10	1·00	0·15	4	
73	G2-2		Miscellaneous pieces.	Black	3·00	1·30	0·30	7	
74	G2-3				1·50	1·00	0·15	2	
75	G2-4				1·50	1·00	0·50	5	
76	G3		Harpoon brass holder.		11·20			20	
76B	G3B				7·50			·12	
77	G4-1		Paper packets.		1·10	0·50	0·20	·8	
78	G4-2								

The marks P and R were no doubt intended to indicate the addition of Platinum or Rhodium to the alloys on which they appear, as was afterwards found to be the case; ♂ is the Zodiac sign for Mars, used also symbolically for the metal iron.

Table III

Balance Sheet Relating to the Disposal of the 79 Faraday Steel Specimens

Also showing the amount of steel used in carrying out the author's research

(A) The grand total of the weight of the specimens before the research was . . . . 3579 grams. (7 lbs. 14 ozs.)

(B) The grand total of the weight of the specimens remaining after the research was . . . . 3016 grams. (6 lbs. $10\frac{1}{4}$ ozs.)

Difference 563 grams. (1 lb. $3\frac{3}{4}$ ozs.)

	Grams.	Lbs.	Ozs.	Per cent.	Grams.	Lbs.	Ozs.	Per cent.
(1) The following Material is still available:								
(A) Untouched portions of the original specimens still remaining	2736	6	$0\frac{1}{2}$	76·5				
(B) Portions cut off:—								
(*a*) for Test-pieces, including trimmings and scrap. The tests comprise: Micrographic examination 46 Specific Gravity . . 21 Hardness . . . . 92 Tensile . . . . . 4 Specific Magnetism . . 22 Electrical Resistance . 3 Dilatometric . . . . 4 Heating and Cooling Curves 3 Corrosion 5	222	0	$7\frac{3}{4}$	6·2	3016	6	$10\frac{1}{4}$	84·3
(*b*) Blades of Miniature Knives	16	0	$0\frac{1}{2}$	0·4				
(*c*) Razor	42	0	$1\frac{1}{2}$	1·2				
(2) The following Sections (C) and (D) represent Material which has been used up and is non-recoverable:								
(C) Drillings (protions of which are still available) from which 434 chemical analyses were made .	187	0	$6\frac{1}{2}$	5·2	563	1	$3\frac{3}{4}$	15·7
(D) Waste in sawing, filing, grinding or turning; also heat and forging waste	376	0	$13\frac{1}{4}$	10·5				
Grand Total, representing the original weight of the 79 specimens . .					3579	7	14	100·0

1 oz. = 28·35 grams.

the examination of the seventy-nine specimens from the wooden box without using more than the percentage of material first stipulated. The actual total weight of drillings used in 434 chemical analyses was only 187 gms. ($6\frac{1}{2}$ oz.) and the total weight of material used for all the tests, including the preparation of specimens for tensile and other tests, amounted only to 222 gms. ($7\frac{3}{4}$ oz.). Table III. shows clearly the amounts of material used for various purposes. It was a somewhat remarkable feat to make so many

analyses and tests, and obtain so much information from such a small quantity of material, and, in doing so, methods of procedure were evolved which should be equally successful and useful in future investigations.

Tests had, in many instances, to be made to detect the presence of from six to seven elements in one specimen, and the actual amounts of each element detected had to be determined. Also, such further tests as could be arranged on these small and difficult specimens were made to determine the mechanical strength and hardness, as well as the electrical and magnetic qualities. During the early stages of the investigation, spectroscopic tests were employed, and these gave considerable assistance in the way of indicating what elements should be determined by chemical analysis. The full information given in Tables V., VII. and VIII. was obtained by chemical analysis and mechanical and physical tests as noted. Superficial inspection alone can reveal nothing of the compositions and nature of steel and alloys, and there is no evidence that anyone had ever done anything more than look at Faraday's specimens during the period of more than a century since he set them aside until the author undertook the research now described.

As one of Faraday's objects was to produce steel alloys of improved quality for fine tools, surgical and other instruments with cutting edges, it would have been specially interesting to test fully the properties of his specimens in this respect. This, however, would have required a large series of experiments demanding a much greater amount of material than that actually available. The author has therefore had to rest content with making a razor and some miniature knives from certain of Faraday's specimens, supplementing this work by an examination of the historic razors, already mentioned.

Curious as are some of the results obtained and some of the compositions revealed by the author's investigations, it is possible to vouch for their accuracy thanks to the high degree of analytical skill, metallographic, physical, mechanical and other knowledge available in the research laboratory of to-day.

It will be seen from Table V. that no high alloys were found among the specimens from Faraday's wooden box. Fortunately, some alloys of this type were found in the further set of specimens from the Science Museum, and the analyses of these are given in Table XVIII. The elements mentioned by Faraday in his writings are tabulated on p. 108, where also the elements found to be present by the author are noted.

Although there is one remarkable alloy steel containing only 0·07 per cent. carbon, the steel and alloys in the wooden box represent generally two classes, about 0·80 to 1·00 per cent. carbon and 1·40 to 1·50 per cent. C., with some specimens of wrought iron. In the papers by Stodart and Faraday, distinction is made between alloys of iron with various elements and those of steel with the same elements. Most of the alloys were made with steel of comparatively high carbon, that being the type of steel used for cutting instruments, which, as Faraday tells us, he was trying to improve by alloying.

The steels used by the firm of Green, Pickslay & Co. for fenders and razors—probably alloys of silver, iridium and rhodium with steel as shown by the letters on p. 133—were most likely of the same general type as the specimens in Faraday's wooden box. No documentary evidence has been found on this point, and no specimens of the Green, Pickslay alloys are known to exist, but commercial considerations render it highly improbable that the firm made any practical use of the high rhodium or platinum steel.

The Hadfield Research on the 79 Early Specimens of Faraday's "Steel and Alloys"

Classification of the Specimens by Visual Examination.—The seventy-nine specimens received by the author are shown in Plate II., just as they were taken out of the box in which they had been preserved, the box being shown in Plate I.

The similarity in form of some of the specimens at once suggested their sorting and classification, which was accordingly carried out after a close visual examination of the specimens individually. As the result it was found convenient to arrange them in lettered groups, allocating to each specimen a group letter and number as shown in Plates XXIX. and XXX. These numbers were stamped on the specimens in small characters, or, where the material proved too hard, added by means of an electric engraving tool. An additional serial number, described in the tables as the Hadfield Research Number, was also allocated to each specimen in order to distinguish them from any marks previously added by Faraday.

In Table II. will be found the individual characteristics of the specimens, determining their classification into groups, with also their weight and dimensions.

By classifying the specimens in this way it was hoped that some indication might be obtained of Faraday's methods of procedure, and possibly of the actual nature of the individual specimens.

This, in fact, proved to be the case, as the following description will show.

The three specimens in Group A termed "Ingots" are evidently of metal which had been allowed to solidify in the crucible from which it had afterwards been removed. These small ingots, as they may be called, do not appear to have been mechanically worked in any way, nor do they show any signs of subsequent heating. They weigh $1\frac{1}{2}$, $3\frac{3}{4}$ and $4\frac{1}{2}$ oz. respectively.

The small excrescence seen on the upper surface of Nos. 1/A.1 and 3/A.3 will be familiar to those having experience in the casting of metals, as due to the evolution of gases on solidification, known in the steel industry as "rising."

From the more irregular form of Specimen No. 2/A.2, as compared with the other two, and the fact that its exterior contour does not conform to the shape of a laboratory crucible, it is to be inferred that probably owing to a somewhat higher temperature being obtained, the crucible deformed during the process of melting, although still being able to retain its contents. In his papers Faraday mentions something of this kind occurring at times.

In Group B, "Blooms," the pieces which weigh approximately 4 to 5 oz. each, are clearly ingots similar to those in Group A but which have been hammered on four sides, probably preparatory to further forging. Adopting the language of the steel industry they have therefore been described for convenience as "blooms." Specimen No. 10/B.7 is somewhat exceptional, a closer examination of which subsequently made indicates that it bears no signs of hammering, but is rather in the nature of Specimen No. 2/A.2, that is, an ingot obtained from a melt in which the crucible has badly deformed owing to its semi-fusion.

The specimens in Group C, "Billets," are definitely forged into more or less rectangular section, and from their individual weights, ranging from $\frac{1}{2}$ to $4\frac{1}{2}$ ozs., might clearly have been derived from ingots such as those in Group A, passing, no doubt, through the stage represented by Group B.

The smaller specimens represented by sub-Groups C.2, 3 and 4 are rather more regular in shape than the larger ones in C.1. Again adopting the nomenclature of the steel industry, the specimens in Group C.1 are conveniently described as "billets," and those in Groups C.2, 3 and 4 as "forgings." A few of the specimens, such as Nos. 12/C.1-1, 13/C.1-2, 14/C.1-3 and 15/C.1-4, are thinned out at one end, indicating that a portion of these specimens has been forged down to some smaller section and parted off.

Specimen No. 20/C.1-9 is rather different from the rest. It has

a truly square section and is fractured at each end; in fact, on seeing it one cannot escape the idea that it may have been broken from a manufactured steel or iron bar. Clearly this does not fit in with Faraday's regular procedure in dealing with his materials after melting. He must, on the other hand, have had available plain or ordinary carbon steel or iron for use as the raw material in the making of his alloys. It must be borne in mind that Faraday speaks of his experiments as relating to "Steel and Alloys" as if the base material of his experiments in certain cases was steel to which special elements were added and in other cases wrought iron was the basis, although only a small number of these are found in the present collection. The size and form represented by this Specimen No. 20/C.1-9 would further be very convenient for packing into the small crucibles used. The possibility that this specimen represents the steel or iron base used in Faraday's experiments on alloy steels has, therefore, been specially considered later in connection with the results of the metallurgical examination.

As regards the specimens of Group D, "Bars," although these are forged bars similar to those in Group C, they are somewhat more regular in their rectangular section, and are distinguished by having one or more sides polished. These seem undoubtedly to represent some of Faraday's attempts in the direction of obtaining alloys suitable for mirrors. The excellence of the mirror polish of Specimen 39/D.12 was, in fact, particularly noticeable, specially too, in view of its having been retained over such a long period of time. It must be remembered that Faraday's specimens were probably stored in a dry atmosphere free from moisture and therefore not severely tested. Undoubtedly, at any rate as regards Faraday's seventy-nine specimens now described, none of these is rust resisting in the true sense of the term.

Prior to the investigation of the specimens as a whole, one was originally selected from the contents of the box for a preliminary examination. This specimen, like No. 39/D.12, had a high mirror polish on one side, and was closely similar in its cross-sectional dimensions. It was therefore included in Group D under the group number D.12.B, and the Hadfield research number 39.B.

Specimen No. 28/D.1, containing 1·59 per cent. C. and 2·36 per cent. Cr., calls for particular comment, its two polished and adjoining faces being most beautifully coloured in a graduation of iridescent tints from blue through purple to a straw colour. The author will have occasion to refer to this specimen in more detail later.

Passing into Group E, Section II., represented by Plate XXX.

a new feature in the form of the specimens appears, that is, this group comprises specimens which have been prepared to certain uniform sizes. The whole of the nineteen pieces in sub-Groups E.1 and E.2 are all, within close limits, $3{\cdot}10 \times 1{\cdot}10 \times 0{\cdot}55$ cm. in dimensions, and have flat surfaces and squared-off ends. The purpose served by these specimens is not readily clear. They may have been blanks for a cutting tool of some kind, for example, a razor or knife blade, with which to determine the practical cutting qualities of the various alloys.

Specimen No. 70/G.1-1, to be referred to later, seems to be a knife blade, probably intended for such a purpose. It would hardly, however, seem necessary for the production of this knife or razor blade to prepare the blanks in such a precise form as that represented by the specimens in sub-Groups E.1 and 2. These specimens would rather seem to have been utilised as a standardised form of test-piece for closer comparison of the effect of a particular operation, say, heat treatments of different kinds, on the various alloys. While undoubtedly they must have been prepared to size after forging, by mechanical preparation of the surface, say, by filing or grinding, some form of heat treatment was evidently applied, giving them their present " black " surface.

An additional feature of these pieces is that there are notches cut into one end, varying from one to three in number in much the same way as nowadays we mark test specimens to indicate differences either in composition or heat or other treatments. This feature proved useful as a further means of classification, as shown both by Plate XXX. and Table II. Reference to it will again be made later, as its possible significance could naturally only be fully discussed after chemical and physical examination of the specimens was used by the author as a means of distinguishing between the specimens of this Group E.

Special note was naturally taken of the presence of any other marks on the specimens which might be of significance, these will be found and entered in Table II. As will be seen later on some of these marks by Faraday are of considerable interest. Of quite frequent occurrence was the mark " P " incorporated with the alchemist's symbol for iron, thus Ⓟ♂ The presence of this mark on the specimens of sub-Group E. 1 was used by the author as a means of separating them from those of sub-Group E. 2 which bore no such marks. With the substitution of the letter " R " for "P," Specimen No. 25/C.3-1, it will be seen, also bears this mark. These signs indicated the presence of Platinum or Rhodium.

To continue with Group E, the three specimens comprising

sub-Group E.3 are similar in form to those of E.1 and E.2, but they have irregular fractured ends. By squaring off these ends they could be brought to similar form, and it seems a fair inference that they are therefore unfinished pieces. They are of the same kind, but in a less finished form.

While having the same characteristic of being prepared in a uniform size, and therefore probably representing some form of test-piece, the specimens in Group E.4 have not the same dimensions as the earlier ones of Group E. They are approximately cubical in shape, being 1·10 cm. square in section, with fractured ends, the length being approximately the same as the sectional dimensions.

Group F contains three specimens labelled " Crude Steel from the Blast Furnace " in handwriting, which is that of Faraday. These are of quite a different character from any of the others in the collection. In cross section they are each 3·10 × 1·20 cm., and they have evidently been fractured from a rectangular bar of this size. Their unwrought surface would further seem to indicate that they are from material melted direct in Faraday's " blast " furnace and cast in a mould of this section. The labels on two of the pieces, Nos. 68/F.2 and 69/F.3, bear the additional word " annealed."

In the final Group G are included the remaining nine specimens; each of these is individual and not classifiable by its form into any of the previous groups.

Reference has already been made to Specimen 70/G.1-1, which is in fact specially interesting, since it is definitely recognisable as a knife blank, the smaller end, which is taper in cross section, forming the blade, and the wider end constituting the tang, which would be fitted into the handle. This specimen besides bearing the mark ♂ has stamped on it the additional word " STOD ART " in two separate parts as shown, a fact which naturally adds additional interest, indicating as it does within the zodiac sign for iron the presence of platinum, also the important fact that the maker of this knife blade was Stodart, the associate of Faraday in his original researches on " steel and alloys."

Specimen No. 71/G.1-2, being also of taper cross section, appears likely to have formed part of a blank intended for some form of cutting tool, and is therefore included with the previous specimen in a special group—G.1. This specimen was, in addition, highly polished over a portion of its surface.

Sub-Group G.2 comprises four very small specimens, one of

which, No. 73/G.2-2, is perforated with small holes in the manner of a wortle plate, such as used for wire drawing, and may conceivably have been intended for this purpose.

Specimen No. 76/G.3 is a complete and well-finished instrument, the purpose of which, in the absence of any record, is difficult to decide. It is in two parts, the spear head and shaft being of steel or iron and fitting by a spring catch into a milled holder, which is of brass. It might be described as a "harpoon" on a small scale.

The collection is completed by two small paper packets, Nos. 77/G.4-1 and 78/G.4-2. They each contain a small quantity, weighing only 0·80 gram, of fine powder, which is not attracted by the magnet. On each of the paper wrappings there is handwriting which is difficult to decipher, but apparently reads "Platina no moment."

Circumstances affecting the Choice of Methods of Examination

Most careful consideration as to the manner in which the examination of this collection of specimens should be carried out was necessary, first, not only because of their importance as relics, but also because of the limited amount of material available. At the same time, there was practically nothing to guide investigation apart from such clues as had been obtained as the result of the preceding classification. Thus the problem presented was specially difficult as except in so far as certain points of similarity or connection between the different specimens might appear during the progress of the chemical and physical examination, nothing short of complete investigation of each individual specimen, both as regards its composition and physical condition, seemed satisfactory.

Physical characteristics could obviously convey little without reference to analysis, without which, in fact, not much real knowledge could be obtained. The determination of chemical composition was therefore regarded as first in importance, specially, too, as it was desired if possible to connect the present specimens with Faraday's own records of his experiments in the alloying of iron and steel.

It was thought the best way to proceed was to make a preliminary examination of one only of the specimens. This, as mentioned, was undertaken on No. 39.B/D.12.B.

The work on this specimen was taken in hand on November 27th, 1930, and after some delays arising from the difficulties of this unusual work, the analysis was completed on December 15th following. Fortunately this, the first specimen selected for

examination, contained the unusual metal which might have been least expected to be present in steel, namely, platinum. Thus this fortunate "find" straightaway gave encouragement to all those concerned that important and interesting results were likely to be obtained from the research, as has proved to be the case.

Methods of Investigation

(*a*) *Specimen No.* 39.B/D.12.B.—The fractured ends of this specimen, which is 11 × 4½ mm. in section and 14 mm. long, indicated that it had been broken from a longer bar, while one of the 14 × 11 mm. faces still retained a mirror polish.

Even more care and consideration as to its economical use was imposed in the present case than for the majority of the specimens, the weight being only 6·066 grams.

Examination of the polished face under the microscope at low magnification showed a high degree of finish in the centre, but scratches on the edges of the surface were so straight and parallel to each other as to render the conclusion fairly certain that the polish had been produced by machine and not by hand. The greater part of the polished surface was free from blemish, but there were small patches on which corrosion had taken place.

That this particular specimen, at any rate, could not be one of those containing any specially high percentage of a heavy precious metal, such as platinum or rhodium, was indicated by the result of the specific gravity determination, which was made on the piece as a whole and gave the figure of 7·81.

The hardness in Brinell numbers, as determined by the diamond pyramid, was 750 on the polished face and 735 on the back of the specimen. Consistently with this the hardness of the specimen on Mohs' scale was found to be 7½ and unfileable, and it would also scratch glass. For the metallographic examination which followed, one of the surfaces was prepared without cutting into the specimen. The microstructure displayed, and shown in photomicros Figs. PM.15 to PM.19, was acicular troosto-martensitic with some austenite, and characteristic of a drastically quenched steel. The hard character of the specimen was rather fortunate than otherwise in connection with the chemical analysis, because although preventing its being drilled, it enabled a sample to be obtained more readily by pounding and in a less wasteful way.

The first chemical determination was made for carbon. This was carried out on a weight of 0·5 gram by combustion with measurement of the volume of carbon dioxide produced.

On a further weight of 0·27 to 0·28 gram determinations of iron

were next made in duplicate by solution in dilute sulphuric acid, removal of metals precipitated by passing hydrogen sulphide and filtration, further reduction by gassing once more, boiling off the H_2S, cooling and titrating with a standard solution of potassuim permanganate.

The washed H_2S precipitate, after ignition, was weighed, and on examination proved to consist chiefly of platinum. On a further portion of 1 gram silicon and platinum were determined quantitatively.

Manganese was determined upon an additional 0·1 gram, also sulphur and phosphorus successively on the same quantity of 2·5 grams. Tests made for chromium and nickel show that the specimen contained neither of these metals. These estimations required 0·5 and 0·25 gram respectively.

Thus the total amount of sample used in the analysis was 5·41 grams, and it had been found possible to determine not only the composition, but the more important of the metallurgical features in the specimen with an expenditure of material of less than one quarter of an ounce.

Thus the practicability of obtaining useful information upon a wide range of properties with a very limited supply of material was demonstrated by the examination of this specimen, and the method of procedure adopted in this case proved generally applicable to the examination of the whole collection of Faraday specimens.

The results of the examination of this first specimen in showing that it contained platinum, and therefore entirely confirming that Faraday had definitely used several of the noble metals in making his experiments, were very encouraging. The results also bore evidence of Faraday's work in the heat treatment and manipulation of his alloys as shown by the state of polish and the hardness of the specimen. Work was therefore continued on the investigation of the remaining specimens. For convenience this work is described under separate heads, according to the method of examination, as follows :—

(*b*) *Chemical Analysis.*—In addition to the interest always attached to a search into the unknown, the greater one afforded by this research in its requiring the breaking of new ground in the methods of analysis has provided one of the most interesting series of problems ever undertaken by the author's chemical staff, who showed great interest in this matter, devoting themselves heart and soul to these investigations of the great philosopher's earliest research work, for this it undoubtedly was.

One of the main difficulties experienced was in the need for constant care to ensure economy in the use of material. Plate XXXI. and the following data will show how efforts in this direction were successful:—

Specimens Analysed.	Determinations Made.	Weight of Drillings Used.
60	434	187 grams

The number of individual analyses for the separate elements is set out in the following table:—

Table IV

Number of Analyses made on the 79 Specimens of Faraday's "Steel and Alloys"

Details of the number of different elements making up the total of 434 analyses carried out:—

		Check Analyses.	Total.
Carbon	57	1	58
Silicon	48	–	48
Sulphur	8	2	10
Phosphorus	12	2	14
Manganese	22	4	26
Chromium	10	1	11
Nickel	20	–	20
Copper	14	1	15
Platinum	32	3	35
Silver	26	3	29
Rhodium	7	4	11
Gold	17	–	17
Precious Metals	27	–	27
Iron	57	56	113
Total	357	77	434

Weight of drillings, portions of these are still available, from which the 434 chemical analyses were made, 187 grams ($6\frac{1}{2}$ ozs.).

The individual quantities of drillings used for each of the determinations were as follows:—

Sulphur	2·50 grams.
Silicon	1·00 gram.
Chromium	1·00 ,,
Copper	1·00 ,,
Platinum, gold, rhodium, and other rare metals.	On the silicon portion of 1 gram.
Carbon	0·50 gram.
Phosphorus	Either on the filtrate from the sulphur or, when done separately, about 0·5 gram.
Iron	0·27 gram.
Silver	0·25 ,,
Nickel	0·25 ,,
Manganese	0·10 ,,

(Note.—1 gram = 0·04 oz. approx. 28·35 grams = 1 oz.)

These and the total amount of drillings used for all the estimations, are shown pictorially in Plate XXXI.

Although the weights used in the analyses were necessarily cut down to the smallest possible amount, a high standard of accuracy has been maintained.

Probably the most important problem which had to be solved was that of ascertaining the most suitable method for determining the iron as the predominant metal present. The ordinary direct method of solution of the sample in dilute sulphuric acid, followed by titration of the ferrous solution with standard potassium permanganate, gave low results with some of the platinum steels, leaving a deficit of 3 or 4 per cent. in the analysis, making a very pronounced obstacle in the progress of the analytical work, and giving rise to much anxiety until a solution of the problem was found. Eventually the difficulty was removed by the method described below.

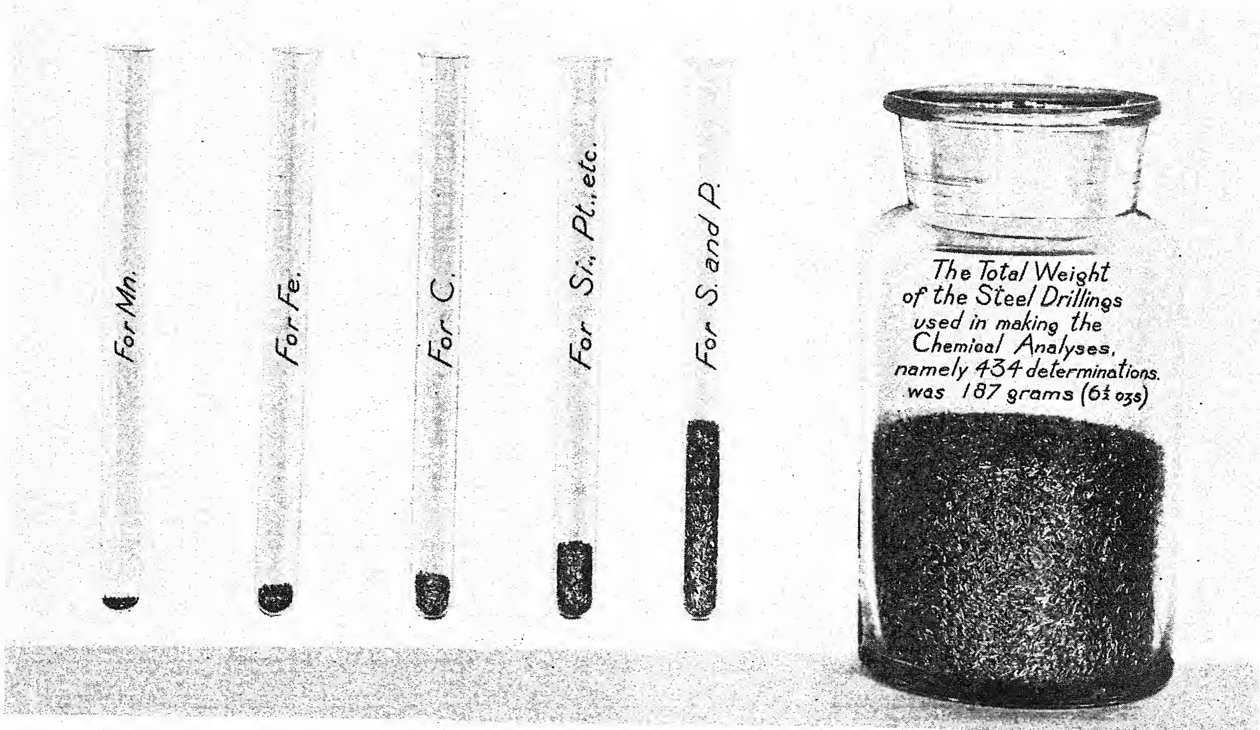
Chemical analysis in a number of cases was preceded by a metallographic investigation. Indications were thus afforded of the approximate carbon percentage, of abnormal proportions of sulphur as in the case of the specimens of Group F and of the metallurgical nature of the material, giving valuable guidance in deciding the course to be pursued in the analysis. Some useful help in the same direction was also obtained from spectrographic examination.

Usually samples for analysis were obtained by drilling. Such a method had the merit of preserving the external contour of the specimen, as well as any significance which may be attached thereto. Where this was not expedient, whether owing to the hardness of the material, or extreme limitation in the amount of material available or other causes, the sample was prepared by pounding in a steel mortar, portions of the material which had previously served for micrographic or other examination being in some cases utilised.

In general, the method adopted was to determine the proportion of carbon and of iron, the two elements known to be present in every case. The sum of these, by the amount of its deficiency from 100 per cent., could, subject to the considerations mentioned below, be taken as an indication of the amount of other elements to be looked for.

Iron.—Many useful indications as to other elements were afforded in its course by the determination of iron. The method adopted was to attack about 0·27 gram, weighed to the nearest ·0001 gram, with dilute sulphuric acid, gently boiling. When

THE TOTAL QUANTITIES OF MATERIAL IN THE FORM OF DRILLINGS USED FOR THE VARIOUS CHEMICAL DETERMINATIONS IN THIS RESEARCH.



0·10 Gram. for Mn. | 0·27 Gram. for Fe. | 0·50 Gram. for C. | 1·00 Gram. for Si, Pt, etc. | 2·50 Gram. for S. and P. | 187 Grams. (About 6½ ozs.)

Three-quarters full size.

[To face p. 156.

visible action had ceased the liquor was inspected. Black insoluble floating matter indicated carbon. There was, however, in many cases an appreciable quantity of a heavy residue. At this stage the liquor was cooled and titrated with $\frac{N}{20}$ permanganate, of which the quantity consumed gave a rough measure of the iron content.

In certain cases the end point was evanescent; this at once indicated that some other element was present and acting slowly. A slight excess of permanganate was added until on boiling a permanent precipitate of manganese peroxide was formed. The solution was next diluted so that it contained 8 c.c. of the sulphuric acid of sp. gr. 1·8 in a total volume of 400 c.c. Hydrogen sulphide was then passed in to saturation, and the liquor heated and allowed to simmer for two minutes. It was then cooled, filtered and washed with 2 per cent. sulphuric acid containing H_2S.

The cold solution was again saturated with H_2S, boiled free from the gas and cooled and titrated with $\frac{N}{20}$ permanganate. The residue upon the filter was ignited and weighed, and afterwards examined for iron by extraction with hydrochloric acid and application of the sulphocyanide test. The amount thus determined, if any, was added to the main proportion determined in the second titration with permanganate, thus giving the total percentage of iron.

In every case the iron determination was made in duplicate. Since 0·27 gram weight of sample was taken, the quality of $\frac{N}{20}$ permanganate required was nearly 100 c.c. In these circumstances a discrepancy of 0·1 or 0·2 c.c. represents an uncertainty of 0·1 or 0·2 per cent. in the iron figure.

Thus the figure for iron is subject to a greater percentage error than that for any one of the other elements, but nevertheless its accuracy was obviously sufficient to preclude the missing of any significant amount of special alloying metal when the total of all elements found exceeded, say, 99·6 per cent. This was nearly always the case, and in view of the fact that direct tests were made to prove the absence of other elements than those actually found and determined, it is seen that the concordant testimony of the two lines of evidence is sufficiently conclusive to establish the substantial accuracy of the analyses.

The precipitate filtered off after adding hydrogen sulphide, including the portion originally insoluble in the sulphuric acid,

disclosed by its examination in different samples the metals copper, gold, silver, platinum and rhodium. Although tests were made for palladium, osmium and iridium, also tin, none of these metals was found.

After ignition the weight of the precipitate just mentioned would roughly indicate the total quantity of the metals referred to except in the case of copper, which would be weighed as oxide. It may be seen therefore that with determinations of iron in duplicate, also of carbon on 0·5 gram, a total weight of very little more than 1 gram was made to yield a large amount of information.

Carbon.—The percentage of this most important element was determined on a weight of sample of 0·5 gram by the process of combustion in oxygen, through measurement of the carbon dioxide produced.

Silicon.—Only slight complication in the usual method for the estimation of silicon was caused by the presence of noble metals. A quantity of 1 gram was attacked with hydrochloric acid until action had ceased. On addition of a few drops of nitric acid the previously insoluble residue of gold, silver, platinum and rhodium, if any, was rapidly dissolved. The solution was then evaporated to dryness, heated on the hot-plate, redissolved in hydrochloric acid and filtered, the residue washed, ignited and weighed in a platinum crucible. After weighing, a little hydrofluoric acid was added to the contents of the crucible and the latter evaporated to dryness, and weighed again. The loss represented silica, from which silicon was calculated in the usual way. The residue and the filtrate were reserved for the determination of the precious metals.

Manganese.—The proportion of manganese in steel is, as is well known, nowadays recognised as being of considerable importance, and its amount was therefore determined in representative members of each group. For this purpose a weight of 0·1 gram was taken and dissolved in dilute nitric acid, the manganese being oxidised with ammonium persulphate in the presence of silver nitrate and the resulting permanganate titrated with sodium arsenite. Usually the permanganate colour produced by the oxidation was so slight as to make titration unnecessary, there obviously being present only traces. The highest amount of manganese found in any specimen was only 0·08 per cent. Thus the metal manganese in Faraday's "steel and alloys" might be termed practically absent.

Special Elements.—The amount of any special elements which might be present in the specimens naturally constituted the chief object and interest from the analytical point of view. The methods employed for their determination were as follows :—

Chromium.—The analytical methods in connection with chromium steels are now well known, and therefore only a brief indication is necessary in this case. One gram of the alloy was dissolved in sulphuric acid, oxidised with nitric acid, boiled, diluted, and the chromium oxidised with potassium permanganate in the usual way. The oxide of manganese was removed by filtration through asbestos, the solution being titrated with standard solutions of ferrous sulphate and potassium permanganate.

Nickel with Detection at the same time of Ag and Cu.—For this estimation a weight of 0·25 gram was dissolved in hydrochloric acid oxidised with nitric acid, diluted, tartaric acid added and the solution neutralised with ammonia, with the addition of the equivalent of 1 c.c. ammonia (·880 sp. gr.) in excess. The solution was cooled, and 2 c.c. of 2 per cent. potassium iodide added.

Where silver was present this was evidenced by a turbidity caused by silver iodide. In any case the solution was then titrated with standard solutions of potassium cyanide and silver nitrate. The net consumption of potassium cyanide was equivalent to any silver, copper and nickel present.

About 0·1 gram sodium peroxide was added to the titrated solution to decompose cyanides, followed by addition of 5 c.c. of 1 per cent. alcoholic solution of dimethylglyoxime. The liquor was next brought to boiling and allowed to cool. The presence of nickel was indicated even in the presence of silver iodide by the characteristic scarlet precipitate.

If in this way more than a trace of nickel was revealed a separate determination was carried out in which the copper and silver were first precipitated by hydrogen sulphide, the solution filtered and the filtrate freed from H_2S and concentrated by boiling. After oxidation with a few drops of nitric acid, tartaric acid was added, the solution was made ammoniacal, potassuim iodide added and titration made with potassium cyanide and silver nitrate.

A very delicate indication is afforded by the turbidity above mentioned, *i.e.*, due to silver iodide. In the conditions stated one drop of $\frac{N}{50}$ silver nitrate solution containing about ·0001 gram of silver produces a quite appreciable turbidity. Detection is thus effected of any silver over 0·04 per cent.

Platinum, Rhodium, Gold, Silver.—The filtrate and residue reserved from the silicon estimation were used to determine the precious metals. The residue, if any, was easily removed from the crucible and was washed into the main filtrate, which was made slightly alkaline with ammonia and then acid with dilute sulphuric

acid so as to contain 2 per cent. of free acid, as in the iron determination. Hydrogen sulphide was passed into saturation, the liquor filtered and the precipitate washed. The filtrate was again neutralised, made faintly acid and gassed once more. A further precipitate was produced here if rhodium was present. When hydrogen sulphide produced no further precipitate the washed sulphides were ignited at about 800° C. The subsequent treatment depended on whether, as described under the titration of nickel, silver was or was not found to be present. In the absence of silver the ignited H_2S precipitate was extracted with hot hydrochloric acid to remove any copper oxide and any traces of Fe_2O_3, and the cleaned metal filtered, ignited and weighed in a porcelain crucible.

The metals were extracted with dilute aqua regia, platinum and gold dissolving. The insoluble metal, if any, was filtered off, ignited, reduced in hydrogen, weighed and identified as rhodium by fusion with potassium hydrogen sulphate solution in water, the characteristic red coloration being produced by addition of hydrochloric acid.

The difference in weight after aqua regia treatment, and where rhodium was present was never more than 0·0005 gram, thus proving the absence of platinum and gold.

In the other cases complete solution was effected by the aqua regia. This solution was evaporated with hydrochloric acid to remove nitric acid, and ammonium chloride added. Ammonium platinic chloride was precipitated if platinum was present, and in such cases the filtrate from this was tested for gold with stannous chloride. No purple coloration was ever found.

On the other hand, where the absence of platinum was shown by no precipitation with ammonium chloride, the purple coloration known as Purple of Cassius was invariably produced on addition of stannous chloride. Thus the material soluble in aqua regia was either platinum or gold, but not both. Indication of the presence of gold was given by the ignited H_2S precipitate after the removal of base metals, its colour in these circumstances being brown.

In the presence of silver the gently ignited metals were extracted with nitric acid, to remove the silver and copper oxide, washed with water and then extracted with hydrochloric acid. The two acid extractions were combined and evaporated to dryness, moistened with one drop of hydrochloric acid and diluted to 10 c.c., and the small precipitate of silver chloride filtered off, dissolved in ammonia and titrated with potassium cyanide and silver nitrate. As described below examination for copper was made on the filtrate from the silver chloride.

The remaining metals free from silver were then ignited and weighed, and extracted with dilute aqua regia as above.

Tests for other Noble Metals.—The ignited hydrogen sulphide precipitate, as described above, was treated with aqua regia. Any platinum was, of course, dissolved. As under some circumstances iridium, when present with a large excess of platinum, may be taken into solution by aqua regia it was necessary to take this into consideration. The precipitate produced by ammonium chloride, however, was always found to be of the pure yellow colour of ammonium platinic chloride. Had there been any iridium present this would have been reddened. The metal insoluble in aqua regia on fusion with potassium bisulphate yielded in all cases a material completely soluble in water. Here also, therefore, iridium was ruled out.

In the case where hydrogen sulphide gave a precipitate it will have been noticed that this was always accounted for by metals other than iridium and osmium, which is always associated with iridium.

To test for palladium the weighed metallic residue obtained by ignition of the purified H_2S precipitate was treated with aqua regia, and the solution freed from nitric acid by evaporation with hydrochloric acid. After dilution potassium iodide was added. The absence of a black flocculent precipitate proved that no palladium was present.

Copper.—Material was afforded for the determination of copper by the analysis of the hydrogen sulphide precipitate obtained during the examination of a 1 gram portion for precious metals, as described above.

After removal of any silver from the acid soluble portion of the ignited precipitate, the solution containing copper, if present, was freed from traces of ferric oxide by ammonia and filtration, made acid with acetic acid, treated with potassium iodide and the liberated iodine titrated with sodium thiosulphate.

In two of the alloys, Nos. 29/D.2 and 34/D.7, large quantities of copper were indicated during the examination of the H_2S precipitate obtained in the determination of iron. The actual amounts were determined by dissolving 1 gram of the alloy in dilute sulphuric acid, precipitating with sodium thiosulphate in the boiling solution, filtering, igniting and removing traces of iron. From this point the procedure was as from the corresponding stage in the method just described.

Sulphur and Phosphorus.—It was important to ascertain the proportion of sulphur and phosphorus, at any rate in a few typical

cases, in order to obtain evidence as to the nature of the material used by Faraday as the base of these alloys.

Additional reasons led to the examination of Specimen No. 68/F.2 for sulphur. The metallographic examination of this specimen showed the presence of sulphides in very large amounts, which suggested the reason for the considerable deficiency in the sum of the carbon and iron percentages, not in this case accounted for by the presence of other metals. Specimen No. 68/F.2 was, in fact, found to contain 1·76 per cent. of sulphur, with similar proportions in Nos. 67/F.1 and 69/F.3.

Sulphur.—The methods employed for sulphur differed according to circumstances, but were in all cases proved to be unaffected by the presence of the noble metals.

In the more usual case where the sulphur content was normal in amount a quantity of 2·5 grams was dissolved in aqua regia, nitric acid removed by evaporation with hydrochloric acid, then silica rendered insoluble and filtered off and the filtrate evaporated until a skin of crystals was formed on the surface. This was just redissolved and 4 c.c. of hydrochloric acid added in excess. The solution was diluted to 70 c.c.; barium chloride was then added to precipitate the sulphur. The precipitate was allowed to settle overnight and was then filtered, washed, ignited and weighed as barium sulphate. By a control test the amount of barium sulphate derived from the reagents was determined and deducted.

Where the sulphur content was abnormal as in the case of Specimens Nos. 67/F.1, 68/F.2 and 69/F.3, it was evolved as hydrogen sulphide and absorbed in cadmium acetate solution. The sulphide in this solution was then titrated with standard iodine and thiosulphate solutions. 0·5 gram of the sample was mixed with 5 grams of a steel containing a known proportion of sulphur. This ensured the volume of hydrogen requisite to carry forward the H_2S, which was passed in series through two columns of cadmium acetate.

Phosphorus.—For this estimation the filtrate from the barium sulphate in the gravimetric determination of sulphur was used. A slight excess of sulphuric acid was added to precipitate the excess of barium, the solution diluted to 250 c.c. filtered, and 200 c.c. of the clear solution collected. This was evaporated to about 70 c.c., ammonia added in slight excess, and the precipitate redissolved in nitric acid. The phosphorus was then precipitated with ammonium nitromolybdate reagent. The yellow precipitate was filtered, washed and titrated with standard sodium hydroxide in excess, and sulphuric acid, using as indicator phenolphthalein.

The purpose of the phosphorus determination was in certain cases to reinforce the evidence from metallographic examination. As in these cases the material resembled wrought iron, a weight of 0·5 gram was used. This was dissolved in aqua regia, evaporated and the residue heated to convert the phosphorus to orthophosphate, redissolved in hydrochloric acid, and the silica removed by filtration. Ammonia in excess was added to the filtrate, followed by nitric acid, the acidity adjusted, and precipitation made with ammonium nitro-molybdate solution. The remaining operations were as described above.

Special Features observed during Chemical Analysis.—With alloys of such unusual compositions as found among these specimens, it is natural that quite special features should be observed during the course of the chemical analysis. It may therefore be of interest to describe some of these.

All the alloys were readily soluble in aqua regia, and on addition of hydrochloric acid those containing platinum, rhodium or gold were quickly attacked, such insoluble residue as remained being easily brought into solution by the addition of nitric acid.

Confirming Faraday's own observations, the effect of dilute sulphuric acid on the alloys containing platinum was very striking. As is well known, with the addition of one volume of strong sulphuric acid to six volumes of water considerable heat is evolved. By allowing 100 c.c. of this warm dilute acid to act upon 0·27 gram of any of the alloys containing platinum, the metal was instantly attacked, leaving after only a few seconds merely a small residue. The alloys containing rhodium or gold, none of which contained platinum, did not behave in this remarkable way, the behaviour being peculiar to the platinum alloys.

Nevertheless, some interesting features were presented in the examination of the alloys containing rhodium. Although the metal itself is insoluble in aqua regia, those of the present alloys which contained rhodium, in fact, all the alloys, as stated above, proved to be easily soluble.

Special treatment was required for the removal of rhodium from a solution containing free sulphuric acid by means of hydrogen sulphide. The complete precipitation of the rhodium was only achieved by the addition of ammonia to the sulphuric acid solution saturated with H_2S, until a considerable quantity of ferrous sulphide was precipitated, this being just dissolved by the addition of dilute sulphuric acid. The whole of the rhodium was precipitated on again saturating with H_2S.

A characteristic appearance was presented by the noble metals

TABLE V

Chemical Analysis (per cent.) of the Specimens Arranged in Groups

1 Hadfield Research Number.	2 Group Mark.	3 Faraday's Own Mark.	11 C.	12 Si.	13 S.	14 P.	15 Mn.	16 Cr.	17 Ni.	18 Cu.	19	20 Au.	21 Ag.	22 Pt.	23 Rh.	24	25 Fe.
GROUP A. (Ingots)																	
1	A-1		0·84	0·22			0·04			0·02							98·78
2	A-2		0·69	0·02										0·80			98·25
3	A-3		0·92	0·28	0·021	0·030	0·05			0·02				0·73			97·90
GROUP B. (Blooms)																	
4	B-1		0·96	0·29			Trace.					Nil	0·15 0·13				98·30
5	B-2		0·92	0·19										0·73			97·90
6	B-3		0·88	0·28	0·048	0·032	Trace					0·61	Nil				98·15
7	B-4		1·33	0·12			Trace						Nil	Trace	0·44 0·40		97·95
8	B-5		1·03	0·31									0·31	1·34	Nil		96·80
9	B-6		0·92	0·33			Trace						Nil	Nil	1·20 1·14		97·35
10	B-7		0·86	0·47			0·04	Nil	0·07 Ni. + Cu				Nil	1·20			97·34
11	B-8		1·10	0·19								0·88	0·15	Nil			97·60
GROUP C. (Billets)																	
12	C1-1		1·24	0·14									0·46 0·35	Nil			97·90
13	C1-2		0·94	0·19			Trace		0·75	0·04			Nil				98·05
14	C1-3		0·94	0·33					0·07 Ni. + Cu.				Nil	0·74			97·60
15	C1-4		0·94	0·30										0·69			98·30
16	C1-5		0·77	0·24								Nil	Nil	Nil			99·10
17	C1-6	1	0·61	0·05								Nil	Nil	2·50			96·70
18	C1-7		0·84	0·33	0·027	0·031			Nil				Nil	0·68			97·90
19	C1-8		1·15	0·24								0·60					97·90
20	C1-9			0·09	0·025	0·032				0·15							
21	C2-1	(F) 2	0·94	0·09										0·75			97·90
22	C2-2		1·06	0·08					2·18	0·03		0·75					96·00
23	C2-3		1·15	0·14								0·90	Trace	Nil			98·11
24	C2-4		0·65	0·09			Trace		2·19	0·07			Nil				96·95
25	C3-1	(R)	0·97	0·19									Nil		1·60		97·50
26	C3-2		0·24			0·107			0·13 Ni. + Cu.				Nil				99·80
27	C-4	2	0·90	0·33									0·26				98·40

TABLE V (*continued*)

Chemical Analysis (per cent.) of the Specimens Arranged in Groups

1 Hadfield Research Number.	2 Group Mark.	3 Faraday's Own Mark.	11 C.	12 Si.	13 S.	14 P.	15 Mn.	16 Cr.	17 Ni.	18 Cu.	19	20 Au.	21 Ag.	22 Pt.	23 Rh.	24	25 Fe.
GROUP D																	
28	D-1		1·59					2·36									96·10
29	D-2		1·05							2·79							96·30
30	D-3		0·93	0·24								Nil	Nil	Nil			99·10
31	D-4		0·07	0·07	0·022	0·108	Trace					Nil	Trace	2·25			97·70
32	D-5		1·09	0·07	0·029	0·051		0·54 0·52	Nil			Nil	Nil	Nil			98·25
33	D-6		0·88	0·33						Trace							98·90
34	D-7		1·30	0·14			Trace	Nil		1·50		Nil	Nil	Nil			97·10
35	D-8		1·44	0·26			Trace			0·08							98·00
36	D-9		1·04	0·15			Trace			Trace							98·60
37	D-10		0·96	0·24			0·04			Trace							98·50
38	D-11		0·94	0·10			Trace			0·12			Trace				98·60
39	D-12A		1·27														98·50
39B	D-12B		1·11	0·13	0·041	0·030	0·05	Nil	Nil	Trace				1·50			97·16
GROUP E.																	
41	E1-1	(P)♂ 3 nicks	1·12	0·14										0·90			97·50
43	E1-3	(P)♂ 3 nicks	1·20	0·16										1·05			97·80
46	E1-6	2 nicks	0·94	0·14								Nil	Nil	1·15	Nil		97·60
47	E1-7	(P)♂ 2 nicks	1·30	0·13								Nil	Nil	1·10			97·30
48	E1-8	P♂ 1 nick															
50	E2-2	3 nicks	1·52	0·09								Nil		Nil			98 16
53	E2-5	2 nicks	1·50									Nil	Nil	Nil			98·40
54	E2-6	2 nicks	1·47														98·30
56	E2-8	2 nicks	1·48	0·07								Nil		Trace			98·27
57	E2-9	1 nick	0·12		0·027	0·124	Trace										99·65
58	E2-10	1 nick	0·07	0·14		0·128											99·20
59	E2-11	1 nick	1·45	0·14					0·10 Ni. + Cu.			Nil	Nil	Nil			98·20
60	E3-1		1·22	0·09			0·06						0·20				98·10
61	E3-2		1·33	0·18										0·80			97·65
62	E3-3		1·05	0·14										1·40			97·34

TABLE V (*continued*)

Chemical Analysis (per cent.) of the Specimens Arranged in Groups

1 Hadfield Research Number.	2 Group Mark.	3 Faraday's Own Mark.	11 C.	12 Si.	13 S.	14 P.	15 Mn.	16 Cr.	17 Ni.	18 Cu.	19	20 Au.	21 Ag.	22 Pt.	23 Rh.	24	25 Fe.
GROUP F.																	
67 68 69	F-1 F-2 F-3	Crude steel from the blast furnace annealed.	1·75	0·10	2·01 1·76 1·73	0·078	Trace		0·06Ni + Cu.								96·60
GROUP G.																	
70 71 76	G1-1 G1-2 G-3	(P)♂ Stodart	 0·95 0·93				 0·07					Nil 1·0		Nil	Nil		99·00 98·00 98·70
STODART SPECIMENS.																	
Scalpel Blade			1·23				0·08										98·70
Old razor with ivory handle .			about 0·80				not over 0·01										99·00

NOTE.—When analysing the samples dealt with in this Table V., in every case careful chemical examination was made to detect the presence of the noble metals, including Palladium, Osmium and Iridium, none of these three elements was found to be present. This note applies also to tin.

With reference to specimens Nos. 40, 42, 44, 45, 49, 51, 52, 55, 63, 64, 65, 66, 72, 73, 74, 75, 76B, 77 and 78, these either formed members of definitely identified groups, or were too small and unimportant to merit full examination. Though not chemically analysed they were subjected to spectroscopic examination.

derived from the ignited H_2S precipitated after the co-precipitated iron, copper, etc. had been removed. The platinum was grey, rhodium greyish-black, and gold earthy brown. On reignition the gold assumed its familiar lustre.

A Study of the Analytical Data.—In Table V. the analytical data thus obtained are completely recorded, the specimens here being placed in their serial order. While the principle was as stated to analyse, where possible, the majority of the specimens for carbon,

TABLE VI

Specific Gravity

Hadfield Research Number.	Group Number.	Specific Gravity.
39B	D. 12.B	7·81
42	E. 1–2	7·82
44	E. 1–4	7·79
45	E. 1–5	7·80
46	E. 1–6	7·84
48	E. 1–8	7·84
49	E. 2–1	7·78
51	E. 2–3	7·79
52	E. 2–4	7·70
54	E. 2–6	7·80
55	E. 2–7	7·80
62	E. 3–3	7·86
63	E. 4–1	7·81
64	E. 4–2	7·81
65	E. 4–3	7·81
66	E. 4–4	7·75
70	G. 1–1	7·83
72	G. 2–1	7·79
73	G. 2–2	7·53
74	G. 2–3	7·79
75	G. 2–4	7·97

iron and any special elements found present, the necessity or otherwise for estimation of other elements was decided from a study of the results as they were obtained during the course of the investigation. This will be made more clear in the comments upon the results generally. The definite association of the marks P and R with a platinum or rhodium content made it reasonably certain that the whole of the specimens of Group E.1 contained platinum, since each of these bore the first of these marks. It was therefore felt that Specimens Nos. 42/E.1-2, 44/E.1-4, and 45/E.1-5 could

with advantage, and on this assumption, be allowed to remain in their original condition. The only possibility seemed to be that these specimens might contain some considerable percentage of platinum greater than that found in Nos. 41/E.1-1, 43/E.1-3, 46/E.1-6 and 47/E.1-7, namely, about 1 per cent. This was safeguarded by the entirely non-destructive determination of specific gravity, which was made on as many of the pieces in the collection as lent themselves to it, as shown in Table VI. The low figures obtained exclude, as will be seen, any such possibility whether as regards the remaining specimens of Group E.1 or any others not chemically analysed.

In view of the very small size of the specimens of Groups E.4 and G.2, it was thought that these could not profitably be investigated much further.

The absence of the special marking referred to naturally does not preclude the presence of platinum or rhodium, nor, of course, of other elements. As regards the specimens of Group E.2, however, since none of the seven analysed specimens contains any special additions, it can reasonably be inferred that of the remaining four, namely, Nos. 49/E.2-1, 51/E.2-3, 52/E. 2-4 and 55/E.2-7, none is alloyed to any appreciable extent, that is, even below a percentage which might sensibly affect a specific gravity determination.

In Table VII. the specimens have for clearer study been reclassified, the alloys being separated from the carbon steels and irons, and grouped according to the alloying metal; the sections are: (1) Carbon Steels and Irons, (2) Binary Steel Alloys, (3) Ternary Steel Alloys.

As regards their carbon content, it is specially noticeable that the specimens divide themselves into two categories. There are first those with low carbon, of which there are four, namely, Nos. 57/E.2-9, 58/E.2-10, 26/C.3-2 and 31/D.4, among those analysed. These range from ·07 to ·24 per cent. The remaining 50, although varying considerably in their carbon content, may all be classed as high, 20 range from ·84 to 1·15 per cent., and 26 from 1·03 to 1·59 per cent. Owing to the special character of the "crude steel" specimens of Group F these are for the moment excluded.

Two of the specimens, Nos. 17/C.1-6 and 24/C.2-4, show by analysis 0·61 and 0·65 per cent. of carbon respectively. In these cases there is a definite explanation for the comparatively low values, since it subsequently proved under micro examination that the surfaces of these pieces were decarburised. The drillings therefore included both low carbon material upon the surface

Table VII

(Section 1)

Chemical Compositions of the Carbon Steels and Irons

Hadfield Research Number.	Group Mark.	C. %	Special Element. %	Fe. %
1	A-1	0·84	—	98·78
16	C1-5	0·77	—	99·10
20	C1-9	—	Cu 0·15	
26	C3-2	0·24	—	99·80
30	D-3	0·93	—	99·10
33	D-6	0·88	—	98·90
35	D-8	1·44	—	98·00
36	D-9	1·04	—	98·60
37	D-10	0·96	—	98·50
38	D-11	0·94	—	98·60
39	D-12A	1·27	—	98·50
50	E2-2	1·52	—	98·16
53	E2-5	1·50	—	98·40
54	E2-6	1·47	—	98·30
56	E2-8	1·48	—	98·27
57	E2-9	0·12	—	99·65
58	E2-10	0·07	—	99·20
59	E2-11	1·45	—	98·20
70	G1-1	0 35	—	99·00
76	Stodart G-3	0·93	—	98·70
			Sulphur.	
67	F-1		2·01	
68	F-2	1·75	1·76	96·60
69	F-3		1·73	

(Section 2)

Classified List of Chemical Compositions of the Binary Steel Alloys

Added Element.	Hadfield Research Number.	Group Mark.	C. %	Special Element. %	Fe. %
Chromium.				Cr	
	28	D-1	1·59	2·36	96·10
	32	D-5	1·09	0·54/·052	98·25

TABLE VII (*continued*)

Section 2 (*continued*).

Added Element.	Hadfield Research Number.	Group Mark.	C. %	Special Element. %	Fe. %
Nickel.				Ni	
	13	C1-2	0·94	0·75	98·05
	24	C2-4	0·65	2·19	96·95
Copper.				Cu	
	29	D-2	1·05	2·79	96·30
	34	D-7	1·30	1·50	97·10
Gold.				Au	
	6	B-3	0·88	0·61	98·15
	19	C1-8	1·15	0·60	97·90
	23	C2-3	1·15	0·90	98·11
	71	G1-2	0·95	1·00	98·00
Silver.				Ag	
	4	B-1	0·96	0·15/0·13	98·30
	12	C1-1	1·24	0·46/0·35	97·90
	27	C-4	0·90	0·26	98·40
	60	E3-1	1·22	0·20	98·10
Platinum.				Pt	
	2	A-2	0·69	0·80	98·25
	3	A-3	0·92	0·73	97·90
	5	B-2	0·92	0·73	97·90
	10	B-7	0·86	1·20	97·34
	14	C1-3	0·94	0·74	97·60
	15	C1-4	0·94	0·69	98·30
	17	C1-6	0·61	2·50	96·70
	18	C1-7	0·84	0·68	97·90
	21	C2-1	0·94	0·75	97·90
	31	D-4	0·07	2·25	97·70
	39B	D-12B	1·11	1·50	97·16
	41	E1-1	1·12	0·90	97·50
	43	E1-3	1·20	1·05	97·80
	46	E1-6	0·94	1·15	97·60
	47	E1-7	1·30	1·10	97·30
	61	E3-2	1·33	0·80	97·65
	62	E3-3	1·05	1·40	97·34

TABLE VII (*continued*)

Section 2 (*continued*).

Added Element.	Hadfield Research Number.	Group Mark.	C. %	Special Element. %	Fe. %
Rhodium.				Rh	
	7	B-4	1·33	0·44/0·40	97·95
	9	B-6	0·92	1·20/1·14	97·35
	25	C3-1	0·97	1·50/1·60	97·50

(Section 3)

Classified List of Chemical Compositions of the Ternary Steel Alloys

Added Element.	Hadfield Research Number	Group Number.	C. %	Special Elements. %	%	Fe. %
Pt and Ag	8	B-5	1·03	Pt 1·34	Ag 0·31	96·80
Ag and Au	11	B-8	1·10	Au 0·88	Ag 0·15	97·60
Ni and Au	22	C2-2	1·06	Au 0·75	Ni 2·18	96·00

layers and high carbon material from the interior. The analytical figures do not, therefore, represent the true carbon content of these steels, which must, in fact, be appreciably higher.

In the case of the small ingot No. 2/A.2, the low value of the carbon content, 0·69 per cent., is no doubt accounted for by excessive heating in the melting operation and the resulting decarburising conditions. The peculiar form of the specimen, it will be remembered, rather definitely suggested this. A similar remark, no doubt, applies to Specimen No. 10/B.7, although the rather higher value of the carbon, 0·86 per cent., would seem to indicate that it has not been so much affected by the abnormal conditions during melting.

It is not surprising to find the majority of Faraday's steels and alloys high in carbon, since practically the only steel known in his day was of that character.

Of the low carbon materials, Nos. 26/C.3-2, and 57/E.2-9 and 58/E.2-10, their high phosphorus content and subsequent micro examination clearly proved them to be of wrought iron.

Although in the case of Specimen No. 26/C.3-2 the carbon content, 0·24 per cent., is rather high for wrought iron, micro examination later showed a typical wrought-iron structure at the centre. There was, however, some carburisation at the corners, possibly due to contact with some carbonaceous material during heating for forging. Since in this case the sample for analysis was taken from the whole cross section of the specimen, it included some of the carburised material.

The production of Specimen No. 31/D.4 with 2·25 per cent. of platinum and with carbon as low as 0·07 per cent., is no mean feat, and must excite the admiration of anyone who has melted steel and knows the difficulties, specially having regard to the simplicity of Faraday's equipment. From the comparatively high phosphorus content of 0·108 per cent. in this specimen it is clear that the base used was wrought iron, either of English or Indian origin. Every metallurgist will agree that, having in view this specimen was produced in 1819, great credit is due to Faraday, who accomplished this with his really wonderful "blast furnace," as he termed it.

Those of the alloys high in carbon which have been analysed are each comparatively low in phosphorus, and except in the case of Specimen No. 32/D.5 remarkably uniform, namely, between 0·030 and 0·032, No. 32/D.5 containing 0·051 per cent. The possibility that No. 20/C.1-9 may represent some of the base material used in making the high carbon steels was therefore made more probable by this fact.

In the circumstances, particular care was taken with this specimen, the sample for analysis being taken by drilling along the central axis so as to preserve the exterior appearance. Prior micro examination of a transverse section, however, disclosed segregation of carbon. It was clear, therefore, that any carbon figure obtained from the drillings could not be truly representative of the material, consequently no analysis of it for carbon was made. This applies also to the iron, the iron percentage being dependent upon variations in the carbon. As in other cases, however, special elements were analysed for, but beyond 0·15 per cent. of copper nothing was found. This small amount of copper the author is inclined to regard as accidental and insufficient to justify the inclusion among the alloy steels of this Specimen No. 20/C.1-9.

Such investigation as has been possible therefore tends to confirm

that this specimen may actually represent some of the base material used by Faraday in his steel and alloy melting experiments. Without extra carburisation of the melt, however, such material would be too deficient in carbon for producing some of the alloys with the highest carbon content as here found. It seems probable therefore that Faraday had at his disposal a selection of different grades of steel varying in their carbon content or "temper," of which this Specimen No. 20/C.1-9 represents only one.

Attention has previously been drawn to Specimen No. 28/D.1, owing to its "iridescent" appearance. This specimen is found to contain, besides a specially high carbon content, 1·59 per cent., also 2·36 per cent. of chromium. There can be little doubt that this is the identical specimen referred to in the joint paper by Stodart and Faraday "On the Alloys of Steel," read in 1822, and in p. 79 of Faraday's book, *Experimental Researches in Chemistry and Physics.* He records, concerning an alloy prepared by melting steel with 3 per cent. of pure chromium, that this after forging, polishing and being acted on by dilute sulphuric acid, gave a very fine damask. After repolishing the damask was restored by heat without the use of acid. Now coloured by oxidation the damasked surface had a novel and beautiful appearance, which was heightened by heating the metal so as to exhibit all the colours from pale straw to blue or from about 430° to 600° F. These remarks are of exceptional interest if only because they provide the only direct information concerning any of the specimens in the present research.

As compared with the 3·0 per cent. of chromium added by Faraday the lower figure of 2·36 per cent. found in this specimen might be expected for two reasons. The chromium metal used by Faraday could hardly have been of the high purity nowadays obtainable, and would not therefore yield its full amount as a constituent of the resulting alloy. There would also inevitably be some loss of the chromium in melting due to oxidation, to which, as is well known by makers of alloy steels, this metal is particularly susceptible. It may be of interest to note incidentally that although the carbon was higher the chromium percentage did not differ much in this specimen from that in the type of steel used about thirty years ago for armour-piercing projectiles.

The foregoing remarks by Faraday led to a closer visual examination of the surface of the specimen, and this revealed, underlying the coloured surface, a delicate mosaic pattern which, without doubt, is the damask effect noted by Faraday. Altogether the

appearance of this specimen is indeed strikingly beautiful. No temper colours on steel which the author has seen have ever quite approached the richness of those produced by Faraday, and one can understand his pleasure in them. Under recent examination this specimen shows that it has retained most beautiful and delicate shades of purple and violet. The author hopes to make further investigations and to present a paper on this interesting specimen.

As regards the specimens of Group F, described as "Crude Steel from the Blast Furnace," as Faraday called the apparatus he used for melting, their composition is interesting, though it is somewhat puzzling as to why these experiments were made. A very high sulphur content of approximately 2 per cent. and specially high carbon would, however, seem to confirm that, unlike the remaining steels, they have been melted direct in Faraday's open blast furnace, that is, not in a crucible. It was to be anticipated that such material would be red-short. This was confirmed by the author, as an attempt was made to forge a small piece from the corner of Specimen No. 68/F.2, the material soon falling to pieces in so doing. The specimen was unforgeable at low, medium or high temperatures. The experiment was probably made in order to determine whether the steels he used could be melted in the open blast furnace without the use of a crucible.

Silver Steels.—In those of the specimens containing silver it will be seen that the proportion of this element never exceeds 0·46 per cent. The explanation of this fact lies in the very limited solubility of silver in steel, as well shown later in the microstruction of Specimen No. 12/C.1.1, where the silver is found as a distinct micro constituent. It will thus be readily understood also why duplicate determinations of the silver content in this specimen showed different amounts.

This same fact did not escape the observant Faraday, who, in his joint paper with Stodart in the *Quarterly Journal of Science*, published in 1820, mentioned that when a mixture of silver and steel was kept long in a molten state, a perfect alloy seemed to be formed; but on solidification, globules of silver appeared on the surface of the button. When a forged bar of this metal was acted on by dilute sulphuric acid the silver was left in threads through the mass, "so that the whole has the appearance of a bundle of fibres of silver and steel as if they had been united by welding."

(*c*) *Determination of Hardness.*—Hardness testing by means of an impression made in the test specimen under load by a diamond pyramid proved particularly useful in the present research. The small size of its impressions was of value in causing less damage to

the specimen and for the higher hardnesses its indications are more reliable than those of the Brinell test made with a hard steel ball.

Advantage was taken of any cut surface or of the region close to a drill hole where the surface had previously been removed, so that the preparation of a smooth surface for the purpose of this test on an unused portion of the specimens was usually unnecessary.

Table VIII. records the results of the hardness determinations in terms of the Brinell scale to which the data obtained had been converted by means of a calibration of the apparatus made for that purpose.

On fourteen of the seventy-five specimens it will be seen that a hardness figure of 600 Brinell or above, indicating a glass-scratching hardness, is obtained. It is thus evident that quenching played a prominent part in Faraday's experimental work. Of these hardened specimens eight are found among the specimens in specially prepared form in Groups E.1 and E.2, thus indicating that these specimens were intended for experiments in heat treatment.

Taking the hardness figures obtained on these groups as a whole, they seem, in fact, to provide further clues in this connection, although not such as to give a complete understanding. The specimens which are over 600 hardness it will be seen are the first four only of each group E.1 and E.2, and these are the ones which have three notches cut in them. The fifth specimen in each group, namely, Nos. 45/E.1-5 and 53/E.2-5, each of which has two notches, are of intermediate hardness, 450 and 460/520 respectively. The remaining members of each group, namely, 6 to 8 in E.1 and Nos. 6 to 11 in E. 2, are of a comparatively low hardness, that is, not exceeding 250. In these, however, definite connection with the marking disappears, because some have two nicks and others only one.

As regards the hardness figures below about 600, owing to lack of information as to the heat treatment which may have been given to the various specimens, these figures are not so useful as they might have been otherwise. Micro examination, as explained later, shows that many of the specimens are in a condition just as forged without further heat treatment. Mainly in connection with this micro examination definite heat treatments, accompanied by hardness measurements, have, however, been carried out by the author, specially in view of the "novelty" of some of the alloys.

The "iridescent" Specimen No. 28/D.1, however, of which an indication of its heat treatment is actually given by Faraday, varies in its hardness from end to end between 630 and 330, no doubt

TABLE VIII

Hardness of the Specimens expressed on the Brinell Scale with their Estimated Tensile Strength

These hardnesses determined by the Diamond Pyramid Hardness test have been converted to equivalent Brinell figures.

Actual tensile specimens from material of over 550 Brinell hardness do not display their full yield strength or tenacity, owing to their tendency to break prematurely, and the tensile data in such cases are therefore shown in italics.

Hadfield Research Number.	Group Number.	Brinell Hardness.	Estimated Tensile Strength. Yield Point. Tons per Sq. Inch.	Estimated Tensile Strength. Maximum Stress. Tons per Sq. Inch.
GROUP A.				
1	A1	262	47	58
2	A2	143 195	20 31	35 45
3	A3	260	47	58
GROUP B.				
4	B1	240	41	54
5	B2	210	34	48
6	B3	234	40	53
7	B4	265	47	58
8	B5	295	54	63
9	B6	268	48	59
10	B7	270	49	59
11	B8	300	55	64
GROUP C.				
12	C1-1	230	39	52
13	C1-2	275	50	60
14	C1-3	230	39	52
15	C1-4	240	41	54
16	C1-5	235	40	53
17	C1-6	730 244	42	55
18	C1-7	314	58	67
19	C1-8	260	47	58
20	C1-9	180	27	42
21	C2-1	250	44	56
22	C2-2	300	55	64
23	C2-3	278	51	60
24	C2-4	276 176 690	50 41 26 *157*	60 54 41 *174*
25	C3-1	260 280	47 51	58 61
26	C3-2	140	19	34
27	C-4	274	50	60
GROUP D.				
28	D-1	330 630	62 *140*	70 *153*
29	D-2	645 395	145 78	158 85
30	D-3	272	49	59
31	D-4	175 180	26 27	41 42
32	D-5	260	47	58
33	D-6	230	39	52
34	D-7	322	60	68
35	D-8	280	51	61
36	D-9	295	54	63

TABLE VIII (*continued*)

Hadfield Research Number.	Group Number.	Brinell Hardness.			Estimated Tensile Strength.					
					Yield Point.			Maximum Stress.		
					Tons per Sq. Inch.					
GROUP D—*continued.*										
37	D-10	286			52			62		
38	D-11	288			53			62		
39	D-12A	560			*120*			*132*		
39B	D-12B	750	735							
40	D-13									
GROUP E.										
41	E1-1	735	688		—		*157*	—		*174*
42	E1-2	740								
43	E1-3	714	664		—		*150*	—		*165*
44	E1-4	745								
45	E1-5	450			92			100		
46	E1-6	250			44			56		
47	E1-7	228			39			52		
48	E1-8	240			41			54		
49	E2-1	720								
50	E2-2	675	414		*153*		82	*169*	89	
51	E2-3	600			*132*			*145*		
52	E2-4	740								
53	E2-5	510	460	520	107	95	110	118	103	121
54	E2-6	200			32			46		
55	E2-7	245			43			55		
56	E2-8	236	230		40	39		53	52	
57	E2-9	128			17			31		
58	E2-10	185	160		28			43		
59	E2-11	196	198		31		31	45	46	
60	E3-1	285	282		52		51	62	61	
61	E3-2	322	288		60		53	68	62	
62	E3-3	320			60			68		
63	E4-1	120			16			30		
64	E4-2	117			16			30		
65	E4-3	140			20			35		
66	E4-4	140			20			35		
GROUP F.										
67	F-1	328			62			70		
68	F-2	230			39			52		
69	F-3	195			31			45		
GROUP G.										
70	G1-1									
71	G1-2	670			*152*			*167*		
72	G2-1	310			57			66		
73	G2-2	435			88			94		
74	G2-3	355			68			75		
75	G2-4	280			51			61		
76	G-3	210			35			48		
76B	G-3B									
77	G4-1									
78	G4-2									

explained by differences of temperature in the tempering operation. There are similar variations between 645 and 395 in No. 29/D.2.

Two other specimens, Nos. 17/C.1-6 and 24/C.2-4, vary in their hardness at different positions. This can be explained by decarburisation of the surface, probably resulting from the heating operations these pieces had experienced either in forging or hardening. In each of these cases the higher hardness figure was taken at the centre of a cut section and the lower on the outer surface.

Of the specimens in Group F., containing high sulphur, Nos. 68/F.2 and 69/F.3, labelled by Faraday as "annealed," are definitely softer than 67/F.1, not so described, the figures being 230 and 195 as compared with 328.

The knife blank specimen, No. 70/G.1-1., has evidently been hardened and tempered ready for final grinding and finishing, the blade portion having a hardness of 470 near the edge and 340/370 at the back. At the remote end of the tang the hardness is only 190.

In Table VIII. accompanying the hardness figures is an estimate of the tensile strength of the specimens as deduced from their hardness. Such an estimate, while fairly closely correct for hardnesses up to 550 Brinell, must necessarily be accepted only as approximate for hardnesses above that figure for the reason mentioned at the head of the table; that is, while the figures given for the very hard specimens probably represent the true approximate yield strength and tenacity of the material, in an actual tensile test, owing to the tendency for the test specimen to break prematurely, such high figures would not be attained.

(*d*) *Metallographic Examination.*—The application of the method of examination by the microscope on polished and etched specimens was specially looked to as likely to afford information of value in the present research. Besides providing for the first time, as far as the author is aware, an opportunity of determining the effect upon the microstructure of steel of additions of the noble metals platinum and rhodium it enabled the response of certain of the special alloys to heat treatment to be investigated, that is, so far as the available specimens permitted.

With the aid of an installation of a new type and design, known as the Hadfield-Beck Metallurgical Microscope also referred to in Chapter IX., a permanent record of the microstructure of typical specimens was obtained as shown in the various illustrations.

The interdependence of the data provided respectively by the chemical and the metallographic methods of examination, as now

used, is well exemplified. Reference has, in fact, already been made, in describing the methods of chemical analysis employed, to the utilisation of information derived from a preliminary examination under the microscope.

The unusual amounts of sulphur in the specimens of Group F have already been particularly referred to. These were first revealed as large inclusions of sulphide under the microscope, leading to their determination by chemical analysis. Typical inclusions of iron sulphide are to be seen in Photomicro Fig. PM.8. No special difficulties were experienced in the preparation of any of the specimens, although this might have been anticipated as regards the etching of the micro sections of the steels containing the precious metals. This did not prove to be the case, and irrespective of composition all the specimens, in fact, etched satisfactorily in the usual reagent, namely, one volume of nitric acid in 100 volumes of ethyl alcohol.

The location of free carbides in all the specimens in which these were present, as judged from other tests, was quite successfully obtained by the use of boiling alkaline sodium picrate, this free carbide being darkened in a similar manner to the cementite in carbon steels.

The mode of occurrence of silver, where this was present, was revealed effectively by a solution of sodium sulphide.

In Table IX., A and B, is given a description of the various microstructures of the specimens examined. Section A refers to the specimens in the condition as received by the author, and Section B records particulars of selected specimens after forging or heat treatment in the author's laboratory.

Figs. PM.1 to 30 illustrate by examples the various structures met with.

Table IX., Section A, shows the microstructure of the specimens examined in the condition as received by the author from the Royal Institution. Taking the various groups in the order of their appearance, the following points seem worthy of comment :—

(1) *Carbon Steels and Irons.*

Wrought Irons.—The microstructure of Specimens 57/E.2-9 and 58/E.2-10 was typical of wrought iron, each containing a large number of slag inclusions as illustrated in Photomicro PM.1 of 57/E.2-9. A chemical determination of the proportion of phosphorus gave ·124 and ·128 per cent. respectively, which is about the usual amount found in wrought iron of ordinary type.

In Specimen 26/C.3-2 there is an irregular carburisation at the

Table IX

Metallographic Examination

Section A.—Specimens in the condition received by the author from the Royal Institution.

Hadfield Research Number.	Group Number.	Analysis. C. %	Analysis. Special Element %	Analysis. Fe. %	Photo-Micrograph Number.	Description of Microstructure.
(1) CARBON STEELS AND IRONS.						
						Wrought Irons.
57	E.2-9	0·12		99·65	P.M. 1	Ferrite grains, and slag. Typical of wrought iron.
58	E.2-10	0·07		99·20		,, ,, ,, ,, ,, ,,
26	C.3-2	0·24		99·80	P.M. 2	Ferrite grains, and slag. Typical of wrought iron but with some irregular carburisation at the surface, chiefly at the corners.
						Carbon Steels.
20	C.1-9	Variable 0·25 to 0·90			P.M. 3 P.M. 4	Variable. Grains of ferrite and lamellar pearlite. Small areas of pearlite only, in the centre.
33	D.6	0·88		98·90	P.M. 5	Granular with traces of lamellar pearlite. A few grains of ferrite.
50	E.2-2	1·52		98·16		Groundmass shows a graduation of tempering structures from troosto-martensite to sorbite. Small globules of free carbide. Grain boundaries outlined by cementite.
56	E.2-8	1·48		98·27	P.M. 6	Groundmass of granular with traces of lamellar pearlite. Numerous spheroids and nodules of free cementite in groundmass and grain boundaries.
						High Sulphur Steel.
68	F.2	1·75	S. 1·76	96·60	P.M. 7 P.M. 8	Coarsely spheroidised carbide in a groundmass of ferrite. Numerous and large inclusions of iron sulphide.

(2) BINARY STEEL ALLOYS.

			Cr.			CHROMIUM STEELS.
32	D.5	1·09	0·54/0·52	98·25		Sorbitic pearlite and spheroidal carbide. Primary grain boundaries indicated by non-metallic inclusions.
28	D.1	1·59	2·36	96·10		Non-acicular troosto-martensitic groundmass. Primary grain boundaries marked by small globules of free carbide, also a smaller grain structure outlined by free carbide.
			Ni.			NICKEL STEEL.
24	C.2-4	0·65	2·19	96·95	P.M. 9	Sorbitic pearlite core with severely decarburised and oxidised surface.
			Cu.			COPPER STEEL.
29	D.2	1·05	2·79	96·30	P.M. 10	Lamellar pearlite.
			Au.			GOLD STEELS.
19	C.1-8	1·15	0·60	97·90		Finely laminated pearlite. Primary grain structure shown by slight segregation.
6	B.3	0·88	0·61	98·15	P.M. 11	Lamellar pearlite with traces of ferrite.
23	C.2-3	1·15	0·90	98·11		Finely laminated and granular pearlite. A little free carbide in the grain junctions.
			Ag.			SILVER STEELS.
4	B.1	0·96	0·15/0·13	98·30		Finely laminated pearlite. Traces of free ferrite. A number of small inclusions, identified as metallic silver, associated with the non-metallic inclusions.
60	E.3-1	1·22	0·20	98·10		Finely laminated pearlite with free carbide in the grain boundaries and as needles within the grains. A few large particles of carbide, the remnants of a eutectic. Some small inclusions of metallic silver.
12	C.1-1	1·24	0·46/0·35	97·90	P.M. 12	Groundmass of ferrite and spheroidal carbide. Some larger particles of carbide located on pre-existing large grain boundaries. Numerous groups of small inclusions of metallic silver.
			Pt.			PLATINUM STEELS.
3	A.3	0·92	0·73	97·90		Finely lamellar pearlite. Occasional unsoundness along grain boundaries.
14	C.1-3	0·94	0·74	97·60	P.M. 13	Granular pearlite. Primary grain boundaries faintly traceable, outlined by nodules of free carbide.
2	A.2	0·69	0·80	98·25	P.M. 14	Grains of ferrite, and of lamellar to spheroidal pearlite. Numerous cavities.
41	E.1-1	1·12	0·90	97·50		Non-acicular troosto-martensite. Shows bands of more troostitic material. Numerous small globules of free carbide. Some large particles of free carbide, the remnants of a eutectic.
43	E.1-3	1·20	1·05	97·80		Very similar to E.1-1.
10	B·7	0·86	1·20	97·34		Finely laminated pearlite, traces of ferrite. Unsoundness along some of the grain boundaries.

TABLE IX (*continued*)

Hadfield Research Number.	Group Number.	Analysis. C. %	Analysis. Special Element %	Analysis. Fe. %	Photo-Micrograph Number.	Description of Microstructure.
(2) BINARY STEEL ALLOYS (*continued*).						PLATINUM STEELS (*continued*).
			Pt.			
39B	D-12B	1·11	1·50	97·16	P.M.15–19	Striated structure. Dark troosto-martensitic groundmass, light striæ of fine acicular martensite. Traces of austenite. Small spheroids of free carbide. The structure is that of a drastically quenched steel.
31	D.4	0·07	2·25	97·70	P.M. 20	Ferrite grains, showing strain lines due to cold work.
17	C.1-6	0·61	2·50	96·70	P.M. 21	Varies from ferrite at the surface to granular and traces of lamellar pearlite, with a little ferrite, in the centre. Unsound and shows cracks. Severely decarburised at the surface.
			Rh.			RHODIUM STEELS.
7	B.4	1·33	0·44/0·40	97·95		Finely laminated pearlite, rather thick grain boundaries of carbide. Local traces of eutectic structure and numerous non-metallic inclusions indicate primary grain boundaries.
9	B.6	0·92	1·20/1·14	97·35		Finely laminated pearlite. A little free ferrite together with non-metallic inclusions and some unsoundness, all indicate the primary grain boundaries.
25	C.3-1	0·97	1·50/1·60	97·50	P.M. 22	Finely laminated pearlite on which primary grain structure is indicated by slight segregation. Non-metallic inclusion chiefly in boundaries of the primary grains.
(3) TERNARY STEEL ALLOYS.						
			Pt. Ag.			PLATINUM-SILVER STEEL.
8	B.5	1·03	1·34 0·31	96·80		Finely laminated pearlite. Small nodules of free carbide, metallic silver and non-metallic inclusions, all lying in primary grain boundaries.
			Au. Ag.			GOLD-SILVER STEEL.
11	B.8	1·10	0·88 0·15	97·60		Grains of finely laminated pearlite. Numerous small inclusions of metallic silver.
			Au. Ni.			GOLD-NICKEL STEEL.
22	C.2-2	1·06	0·75 2·18	96·00	P.M. 23	Finely laminated and granular pearlite. Slight segregation indicates primary grain structure. Non-metallic inclusions of usual appearance.

TABLE IX (*continued*)

SECTION B.—Selected specimens after forging or heat treatment by the author.

Hadfield Research Number.	Group Number.	Analysis. C. %	Analysis. Special Element %	Analysis. Fe. %	Photo-Micrograph Number.	Treatment.	Hardness by Diamond Pyramid Test. Brinell Scale. As received.	Hardness by Diamond Pyramid Test. Brinell Scale. After Treatment.	Description of Microstructure.
			Au.						GOLD STEEL.
6	B.3	0·88	0·61	98·15	P.M. 24	Heated to 800° C. and cooled in air.	234	270	Lamellar pearlite and grains of ferrite. Similar to condition as received.
			Pt.						PLATINUM STEELS.
14	C.1-3	0·94	0·74	97·60	P.M. 25	Forged from $\frac{9}{16} \times \frac{1}{2}$ in. to $\frac{3}{16} \times \frac{3}{16}$ in cross section.	230	350	Lamellar pearlite. Pearlite was granular as received.
17	C.1-6	0·61	2·50	96·70	P.M. 26	Heated to 800° C., and cooled in air.	330	325	Very fine granular pearlite, with traces of lamellar pearlite and of free ferrite. Similar to condition as received.
17	C.1-6	0·61	2·50	96·70		Heated to 800° C. and cooled in air. Heated to 1100°C. and quenched in water.	330	710	Moderately coarse acicular martensitic structure. No austenitic grains or free carbide.
			Rh.						RHODIUM STEEL.
25	C.3-1	0·97	1·50/1·60	97·50	P.M. 27	Heated to 800° C. and cooled in air.	280	240	Very fine lamellar pearlite. Similar to condition as received.
25	C.3-1	0·97	1·50/1·60	97·50	P.M. 28	Heated to 800°C. and cooled in air. Heated to 800° C. and quenched in water.	280	735	Fine, slightly acicular groundmass. Very small spheroids of carbide distributed throughout the mass.
25	C.3-1	0·97	1·50/1·60	97·50	P.M. 29	Heated to 800° C. and cooled in air. Heated to 1100°C. and quenched in water.	280	760	Moderately coarse acicular martensitic structure, with a few isolated austenitic grains. No free carbide remaining.
			Au. Ni.						GOLD-NICKEL STEEL.
22	C.2-2	1·06	0·75 2·18	96·00	P.M. 30	Heated to 800° C. and cooled in air.	300	315	Very finely lamellar pearlite. Similar to condition as received.

surface, due to some unknown cause near two opposite corners of the rectangular cross section, as shown in Photomicro PM.2. Otherwise the material resembles wrought iron of ordinary type.

Carbon Steels.—The microstructure of Specimen 20/C.1-9 showed that it was not homogeneous. In a few small areas in the centre the only constituent was pearlite, and the proportion of carbon would therefore be about 0·9 per cent., but the structure of the rest was that of a 0·25 to 0·40 per cent. carbon steel. The photograph Fig. PM.4 shows a complete cross section at 2 magnifications of this specimen, in the centre of which can be clearly seen the carbon segregation.

No special comment is called for in the case of the remainder of the carbon steels, which are illustrated by Figs. PM.5 and 6.

High Sulphur Steel (Figs. PM.7 and 8).—In Specimen 68/F.2, containing 1·76 per cent. of sulphur, although the material contains only a trace of manganese, the sulphide exists in globular aggregates and not in films. It is also specially interesting to find in this material, which contains 1·75 per cent. of carbon, a complete disintegration of the pearlite into free cementite.

(2) *Binary Steel Alloys.*

Chromium Steels, Nickel Steels, Copper Steels.—No special comment is necessary as regards the microstructures of these specimens, which are quite typical of their classes. Fig. PM.9 illustrates No. 24/C.2-4 (2·19 Ni), and Fig. PM.10 shows No. 29/D.2 (2·79 Cu), in which the structure is seen to consist merely of lamellar pearlite.

Gold Steels.—The three examples, of which a photomicrograph of No. 6/B.3 is illustrated in Fig. PM.11, show no feature which distinguishes them from carbon steels of the same proportion of carbon. It is inferred, therefore, that gold in quantities increasing to 0·90 per cent. does not appreciably alter the eutectoid proportion of carbon, and, further, it is completely soluble in steel.

Silver Steels.—The particular interest of these specimens was the existence of the silver as a separate micro constituent. On first examining one of these specimens, some particles were noticed among the non-metallic inclusions, which became bright when the stage of the microstructure was racked a little out of focus. When in focus, the particles were mottled and of a yellow colour. In shape they were generally elongated. The chemical analysis had indicated that the specimen contained silver, and on etching the polished specimen with a solution of sodium sulphide many particles among the inclusions were blackened. It may be noted that in Specimen No. 4/B.1. containing only 0·13 per cent. of

REPRESENTATIVE PHOTOMICROGRAPHS FROM THE SEVENTY-NINE SPECIMENS

(A) As Received.

Group 1.—Carbon Steels and Irons

Plate.	Photomicrograph Number.	Specimen Number.
XXXII.	PM. 1	57/E. 2–9
	PM. 2	26/C. 3–2
	PM. 3, PM. 4	20/C. 1–9
XXXIII.	PM. 5	33/D. 6
	PM. 6	56/E. 2–8
XXXIV.	PM. 7, PM. 8	68/F. 2

Group 2.—Binary Alloy Steels

Plate.	Photomicrograph Number.	Specimen Number.
XXXV.	PM. 9	24/C. 2–4
	PM. 10	29/D. 2
XXXVI.	PM. 11	6/B. 3
	PM. 12	12/C. 1–1
XXXVII.	PM. 13	14/C. 1–3
	PM. 14	2/A. 2
XXXVIII.	PM. 15, PM. 16	39B/D. 12B
XXXIX.	PM. 17, PM. 18	39B/D. 12B
XL.	PM. 19	39B/D. 12B
	PM. 20	31/D. 4
XLI.	PM. 21	17/C. 1–6
	PM. 22	25/C. 3–1

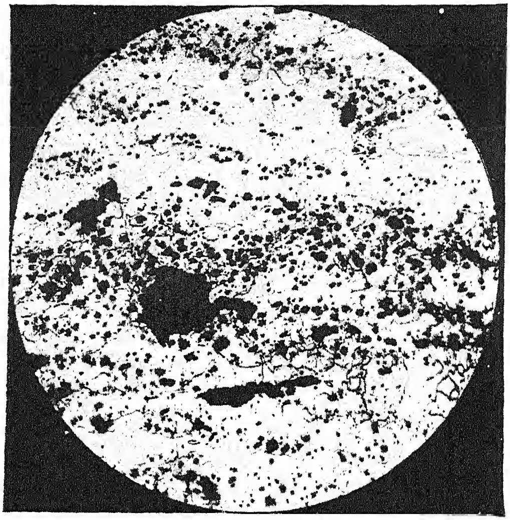
Group 3.—Ternary Steel Alloys

Plate.	Photomicrograph Number.	Specimen Number.
XLII.	PM. 23	22/C. 2–2

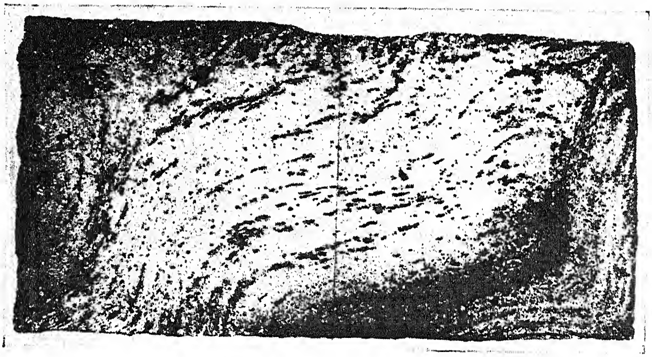
(B) As Heat-treated by the Author

Plate.	Photomicrograph Number.	Specimen Number.
XLIII.	PM. 24	6/B. 3
	PM. 25	14/C. 1–3
XLIV.	PM. 26	17/C. 1–6
	PM. 27	25/C. 3–1
XLV.	PM. 28, PM. 29	25/C. 3–1
XLVI.	PM. 30	22/C. 2–2

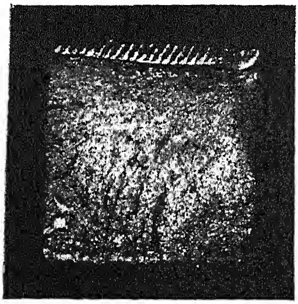
[To face p. 184.



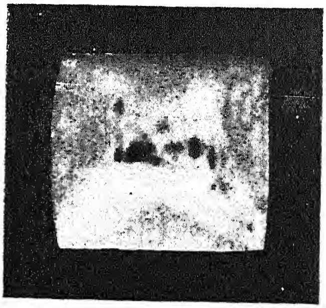
PM. 1. (X 80.)
57/E. 2–9.
C ·12. S ·027. P ·124 %.
WROUGHT IRON.



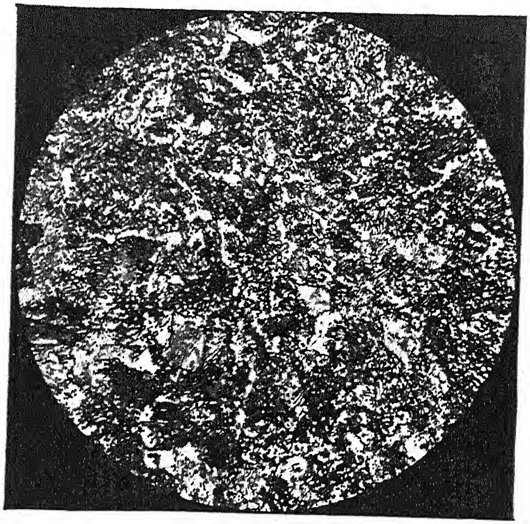
PM. 2. (X 12.)
26/C. 3–2.
C ·24 %.
WROUGHT IRON. CARBONISED AT THE CORNERS.



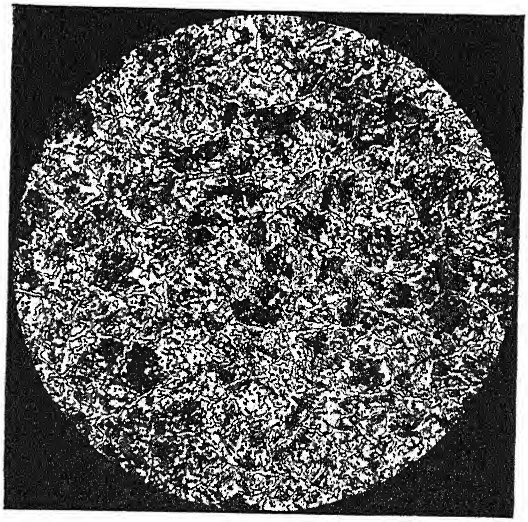
PM. 3. (X 2.)
20/C. 1–9.
FRACTURE. CARBON STEEL.



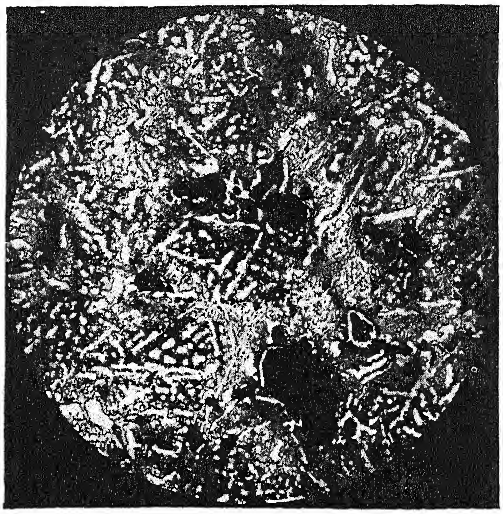
PM. 4. (X 2.)
20/C. 1–9.
CARBON STEEL.



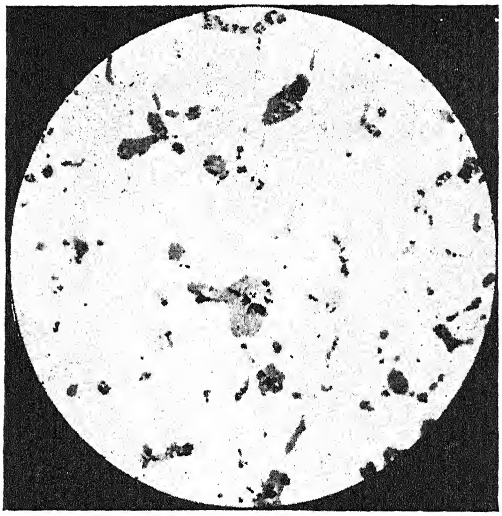
PM. 5. (X 400.)
33/D. 6.
C ·88 %.



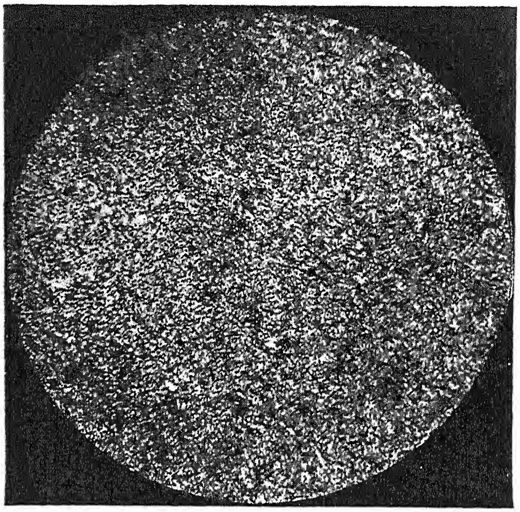
PM. 6. (X 400.)
56/E. 2–8.
C 1·48 %.



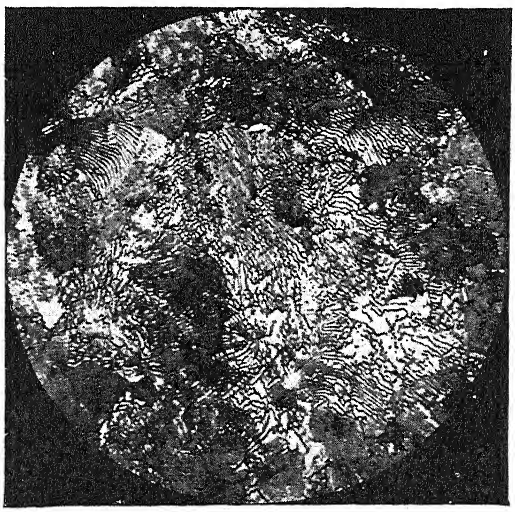
PM. 7. (X 200.)
68/F. 2.
C 1·75. S 1·76 %.
POLISHED AND ETCHED.



PM. 8. (X 200.)
68/F. 2.
C 1·75. S 1·76 %.
AS POLISHED.

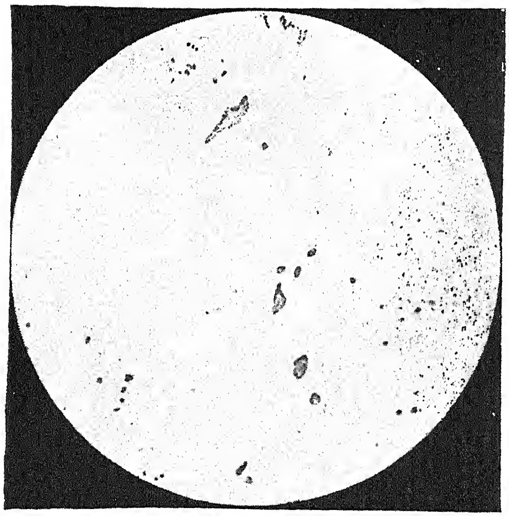


PM. 9. (X 400.)
24/C. 2–4.
C ·65. Ni 2·19 %.



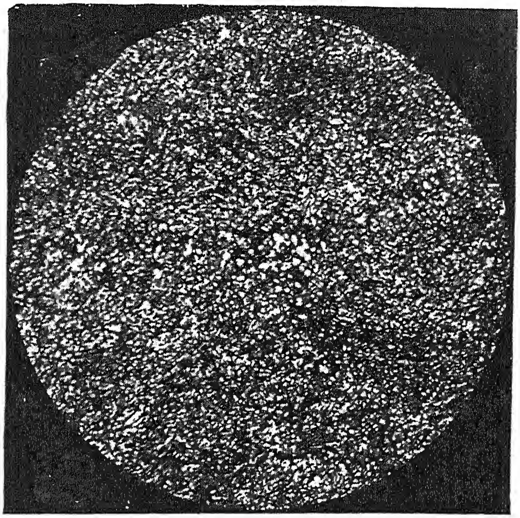
PM. 10. (X 400.)
29/D. 2.
C 1·05. Cu 2·79 %.

PM. 11. (X 400.)
6/B. 3.
C ·88. Au ·61 %.

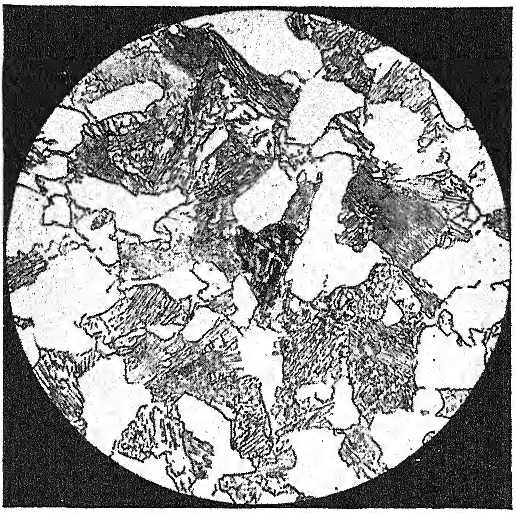


PM. 12. (X 400.)
12/C. 1–1.
C 1·24. Ag $\left\{ \begin{array}{l} \cdot 35\ \%. \\ \cdot 46\ \%. \end{array} \right.$

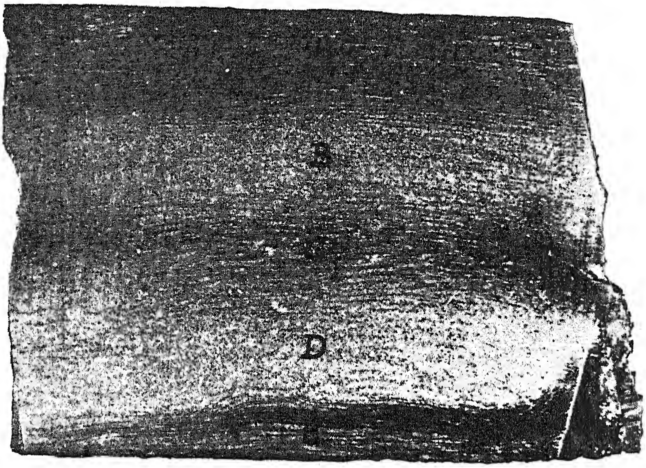
AS POLISHED, SHOWING SILVER INCLUSIONS.



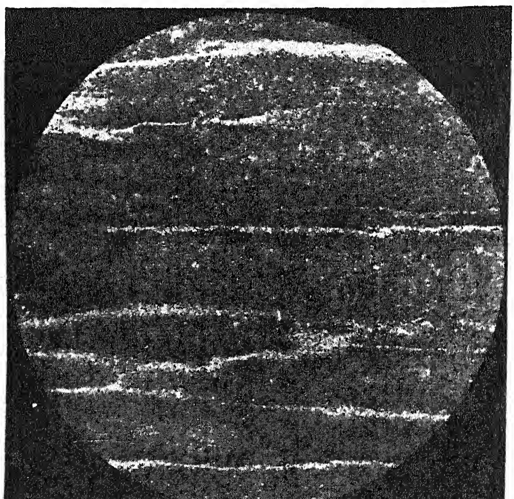
PM. 13. (X 400.)
14/C. 1–3.
C ·94. Pt ·74 %.



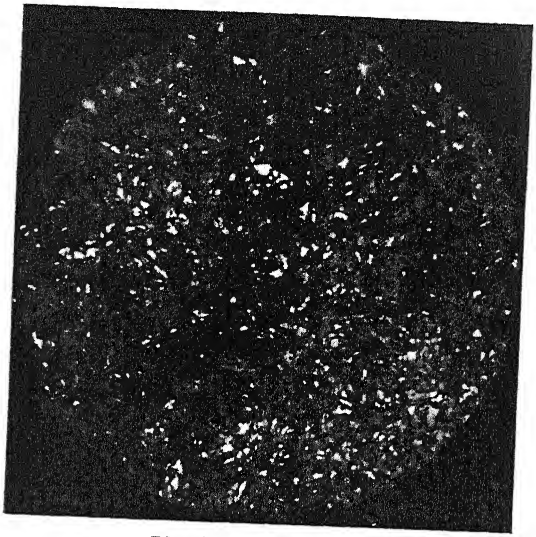
PM. 14. (X 400.)
2/A. 2.
C ·69. Pt ·80 %.



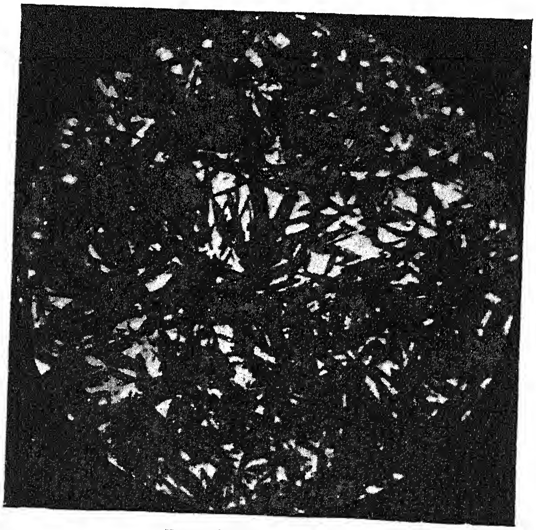
PM. 15. (X 4·8.)
39B/D. 12B.
C 1·11. Pt 1·50 %.
Photomicrograph of Polished and Etched Surface.



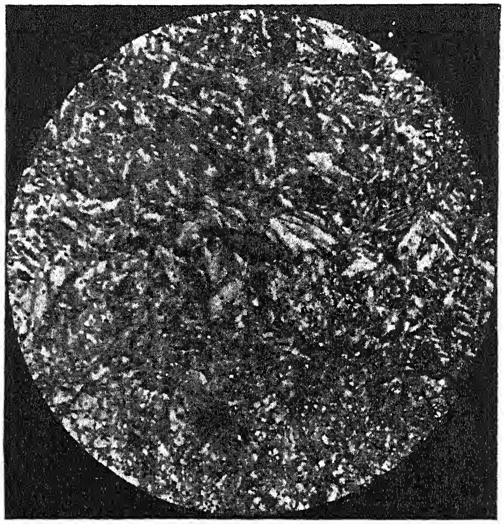
PM. 16. (X 80.)
39B/D. 12B.
C 1·11. Pt 1·50 %.
Zone C.



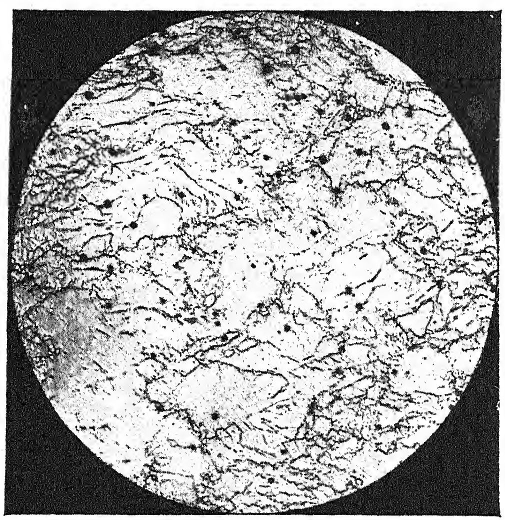
PM. 17. (X 1200.)
39B/D. 12B.
C 1·11. Pt 1·50 %.
ZONE A.



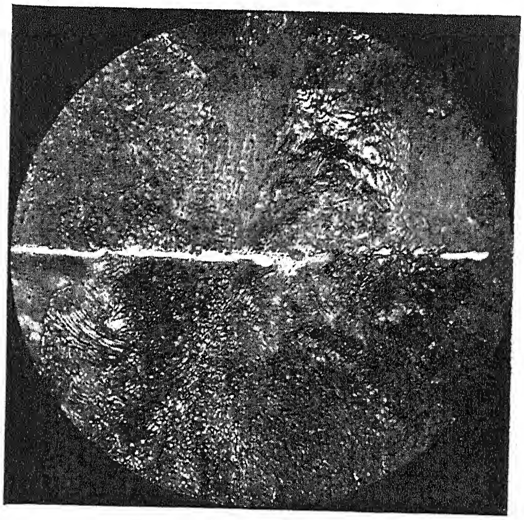
PM. 18. (X 1200.)
39B/D. 12B.
C 1·11. Pt 1·50 %.
ZONE D.



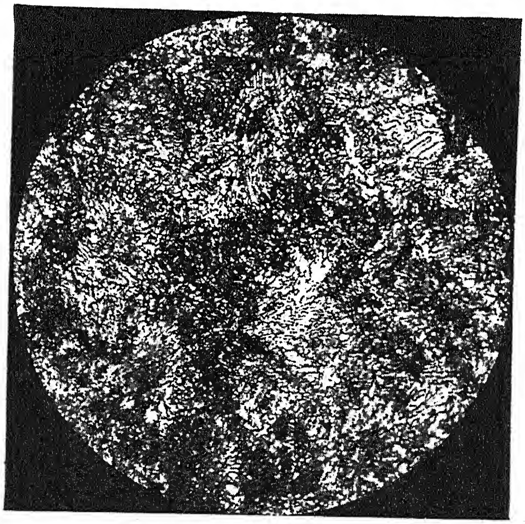
PM. 19. (X 1200.)
39B/D. 12B.
C 1·11. Pt 1·50 %.
A Light Etching Band in Zone C.



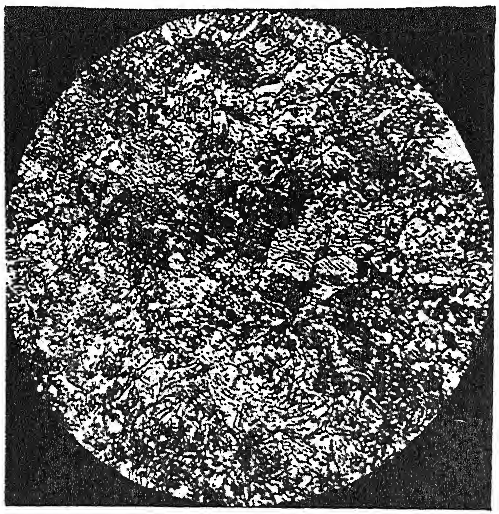
PM. 20. (X 80.)
31/D. 4.
C ·07. Pt 2·25 %.



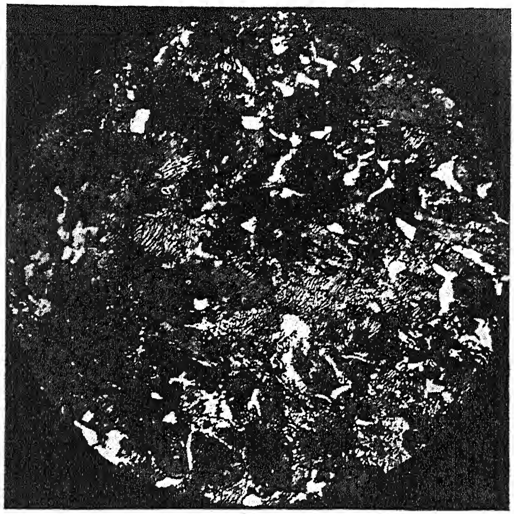
PM. 21. (X 400.)
17/C. 1–6.
C ·61. Pt 2·50 %.



PM. 22. (X 400.)
25/C. 3–1.
C ·97. Rh 1·60 %.

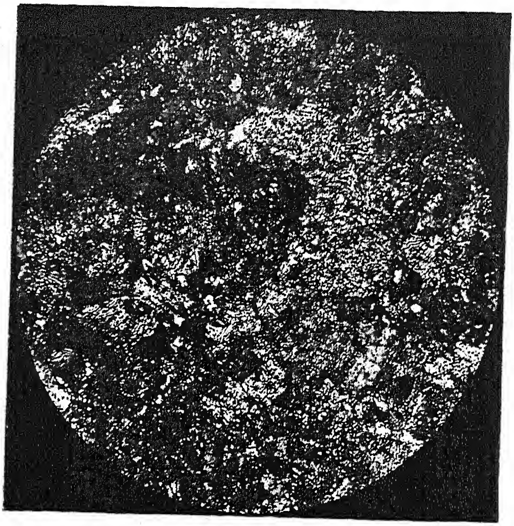


PM. 23. (X 400.)
22/C. 2–2.
C 1·06. Ni 2·18. Au ·75 %.

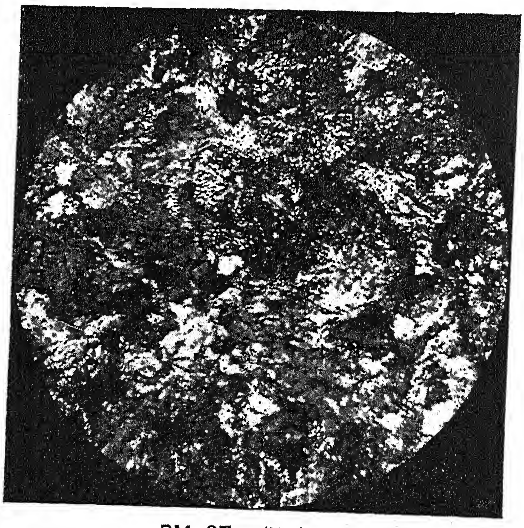


PM. 24. (X 400.)
6/B. 3.
C ·88. Au ·61 %.
HEATED TO 800° C. AND COOLED IN AIR.

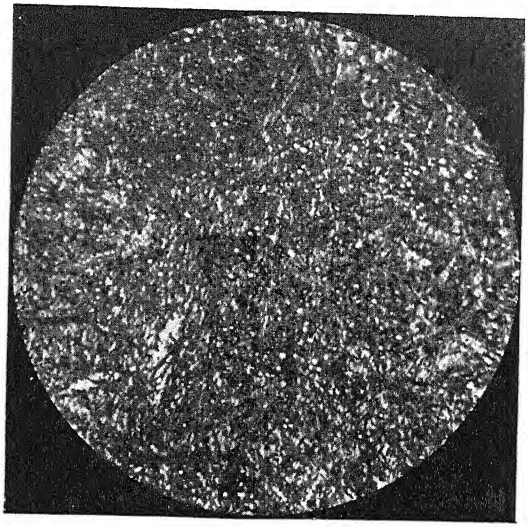
PM. 25. (X 400.)
14/C. 1–3.
C ·94. Pt ·74 %.
AS FORGED BY THE AUTHOR.



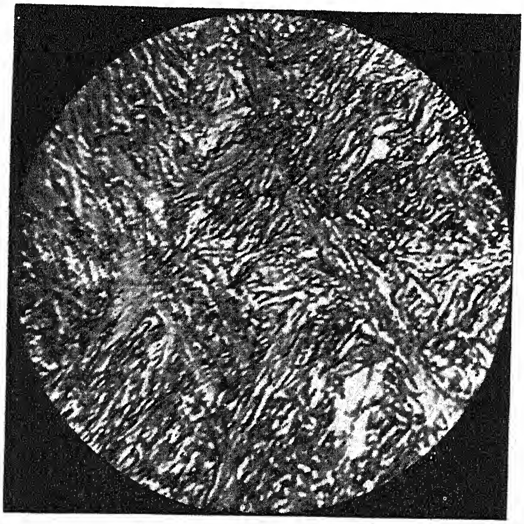
PM. 26. (X 400.)
17/C. 1–6.
C ·61, Pt 2·50 %.
HEATED TO 800° C. AND COOLED IN AIR.



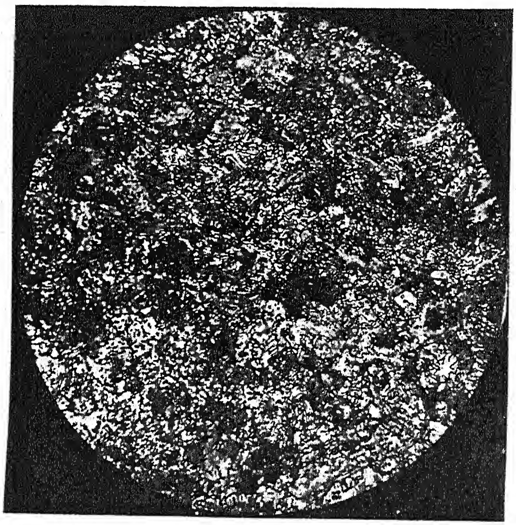
PM. 27. (X 400.)
25/C. 3–1.
C ·97. Rh 1·60 %.
HEATED TO 800° C. AND COOLED IN AIR.



PM. 28. (X 1200.)
25/C. 3–1.
C ·97. Rh 1·60 %.
HEATED TO 800° C. AND COOLED IN AIR, THEN HEATED TO 800° C. AND QUENCHED IN WATER.



PM. 29. (X 1200.)
25/C. 3–1.
C 97. Rh 1·60 %.
HEATED TO 800° C. AND COOLED IN AIR, THEN HEATED TO 1100° C. AND QUENCHED IN WATER.



PM. 30. (X 400.)
22/C. 2–2.
C 1·06. Ni 2·18. Au ·75 %.
HEATED TO 800° C. AND COOLED IN AIR.

this metal, inclusions of silver were found. Fig. PM.12, which is a photomicrograph of Specimen No. 12/C.1-1 polished, but unetched, shows a number of silver inclusions. It may be concluded, therefore, that the solubility of silver in high carbon steel is very low. The observations made by Faraday in connection with his experiments on melting silver with steel have already been referred to.

Platinum Steels (Figs. PM.13-21).—In none of the specimens examined containing platinum in amounts up to 2·50 per cent. has this element given any indication in the microstructure of its presence. Even in the Specimen No. 31/D.4, containing only 0·07 per cent. of carbon and 2·25 per cent. of platinum, ferrite and non-metallic inclusions are the only micro constituents visible (see Fig. PM.20). Platinum, at any rate, in amounts up to about 2·50 per cent. is therefore soluble in either low or high carbon steel. The low carbon in this Specimen No. 31/D.4 made it particularly interesting, giving rise to some speculation both as to the base used and the method of its manufacture. All that can be said on this point as a result of the micro examination however is, that if, as seems probable from the high phosphorus content, it was made from wrought iron, the act of melting has removed the major proportion of the slag inclusions present in the latter, which is quite an interesting point.

Specimens Nos. 41/E.1-1 and 43/E.1-3 possessed the characteristic structures of hardened steels, the remainder indicated the ordinary unhardened condition. Further reference is made to this point in describing the structure after heat treatment.

Specimen No. 17/C.1-6 (Fig. PM.21), containing the highest proportion of platinum, was unfortunately found to be severely decarburised at the surface, thus reducing its value for investigatory purposes. It was, however, submitted to an experimental quenching treatment, the results of which are described later.

A general description of the microstructure of Specimen No. 39B/D.12.B, has already been given in the special account of the investigation of it in pp. 153 and 154. Partly because this was the first specimen examined, but also because the micro examination showed the structure to be very much segregated, a series of photomicros was prepared from this specimen and is shown in Figs. PM.15 to 19. The following is a detailed description of these photomicrographs :—

Fig. PM.15, taken at 4·8 magnifications, illustrates the structure over the whole surface of one face of this small specimen, and clearly shows the laminated and heterogeneous character of the structure.

This resolves itself into a number of zones, each of which has been lettered for easier reference in the description of the subsequent photomicrographs taken at higher magnifications.

The microstructure of Zone C, at 80 magnifications, is shown in Fig. PM.16, and consists of a dark ground mass of fine troosto-martensite and light striæ of acicular martensite with little spheroids of free carbide. The photomicrograph at 1200 magnifications taken of an area in one of the white striæ above mentioned is shown in Fig. PM.19. The acicular character of the structure is more clearly seen at this magnification, as are also the little white spheroids of free carbide. The inclusion in the centre of the field is sulphide of iron.

Fig. PM.17 illustrates the structure of Zone A at 1200 magnifications, and is also typical of the dark etching constituent in Zones C and E. The structure consists of fine acicular troosto-martensite with traces of austenite which appear white. Zone D, from which Fig. PM.18 is taken, is a beautiful example of acicular austenite and martensite. Other examples of this structure are found in the groundmass of Zone B.

The microstructure of this Specimen 39.B/D.12.B in its general character represents that of a drastically quenched steel.

Rhodium Steels.—The microstructures of these specimens, illustrated by Fig. PM.22, show that rhodium in proportions up to about 1·50 per cent. has not affected the microstructure of high carbon steel when in the pearlitic condition. Thus, to this extent at least, rhodium is soluble in steel. Some experiments of the effect of hardening treatments on the microstructure are referred to a little later.

(3) *Ternary Steel Alloys.*

Platinum-Silver Steel, Gold-Silver Steel.—In both of these specimens metallic silver was found as inclusions, otherwise their microstructure did not call for special comment. The gold-silver steel No. 11/B.8 contained 0·88 per cent. of gold, and as little as 0·15 per cent. of silver. Owing to the solvent action which platinum and gold have upon silver, it might have been expected that they would have facilitated the solution of silver in the steel. This, however, has evidently not been the case.

Gold-Nickel Steel (Fig. PM.23).—No modification of the microstructure has been caused by the gold.

Non-Metallic Inclusions.—From the fact that the non-metallic inclusions found in the specimens examined in this research were generally attacked by sodium picrate, it may be inferred that they

are chiefly sulphide inclusions, and from the practical absence of manganese must consist of ferrous sulphide. Their colour is grey brown, while inclusions of manganese sulphide are dove grey. Except in the high sulphur steels their amount was not excessive.

Segregation.—A marked degree of segregation resulting from the mode of primary solidification was found in the specimens generally. Different areas are differently coloured or toned as a result of the attack of the etching reagent. The type of segregation met with is illustrated in Photomicrographs PM.15 and 16 of specimens 39.B/D.12B., taken at 4·8 and 80 magnifications.

Table IX., Section B shows the microstructure of the specimens after forging or heat treatment in the author's laboratory.

Forging.—Only one specimen, No. 14/C.1-3, containing 0·94 per cent. carbon and 0·74 per cent. platinum, was examined after experimental forging. Although the reduction effected in the cross section was in the ratio 9 : 1 no significant change in the microstructure resulted, as will be seen by comparison of Fig. PM.25 with Fig. PM. 13. It may be fairly concluded, therefore, that in its initial condition as received the specimen was also in the forged condition.

Heat Treatment.—The effect of various alloying elements upon the microstructure can naturally only be determined properly from specimens which have undergone similar heat treatment. The microstructure of the specimens as received in most cases suggested that the specimens had been cooled in air. A representative of each of the gold, platinum, rhodium and gold-nickel alloys was therefore taken and submitted to the heat treatment known as "normalising," that is, heating to 800° C., allowing to attain thermal equilibrium, followed by cooling in the air. The small pieces used in this research were maintained for five minutes at 800° C. It will be seen from the Table IX. and Photomicros PM.24, 26, 27 and 30 that in every case the structure resulting from this treatment was similar to that in the condition as received by the author. It would seem, therefore, that these particular alloys, which had a pearlitic microstructure, had in the final operation performed on them by Faraday been cooled freely in the air from a temperature exceeding at least 800° C.

Effect of Quenching Treatments on the Microstructure.—Two of the alloyed steels were further selected for test as to their response to hardening in the quenching operation as gauged by effect on the microstructure. Specimen 25/C.3-1, containing 0·97 per cent. of carbon and 1·50 per cent. of rhodium, was selected as one of these,

and three test-pieces (*a*), (*b*), (*c*) cut from it of equal size. All were normalised, (*b*) was then heated to 800° C. and quenched in water, and (*c*) was heated to 1100° C. and quenched in water. The respective microstructures after the treatments shown in Figs. PM.27, 28 and 29 resembled those of a carbon steel having the same carbon content. Very few austenitic grains were to be seen in the structure of the piece quenched from 1100° C. The hardness figures shown in the table and determined on the actual micro section from each of the treated specimens showed effects produced by the treatments consistent with the microstructure. The conclusion previously arrived at that rhodium in proportions up to 1·5 per cent. has no effect on the microstructure of carbon steel may therefore be extended to include either rapid or slow cooling.

No. 17/C.1-6, the other specimen selected for quenching treatment, contained the highest amount of an alloying noble metal of any of the seventy-nine specimens, that is, 2·50 per cent. of platinum. Unfortunately, it was badly decarburised, though this did not interfere with the single experiment carried out. This consisted of heating a specimen to 1100° C. followed by quenching in water. Both the microstructure and the hardness of the specimen after this treatment gave similar results to those which would be obtained with carbon steel of similar percentage of carbon under the same treatment. A similar conclusion may therefore be arrived at as in the case of rhodium; that is, platinum, in this case up to 2·50 per cent., has no marked effect on the microstructure of steel even under varied conditions of the rate of cooling.

(*e*) *Resistance to Corrosion.*—It seemed very desirable to carry out such corrosion tests as were possible upon the specimens, since it is known that one of Faraday's objectives in his research on alloy steels was to obtain a non-corrodible steel, or at any rate one which would make untarnishable mirrors.

Special interest attached to the steels containing platinum or rhodium, since such indications as existed in the records of any success Faraday may have had in this direction point to their having resulted from the addition of these metals. For his own tests, therefore, the author's selection was made from these alloys, including also one of the plain carbon steels in the collection, No. 50/E.2-2.

Standard materials of known characteristics were necessary as a basis of comparison, and these were furnished by specimens of mild steel of modern manufacture, with also a well-known brand of ingot iron, as shown in Table X.

Table X

Tests for Resistance to Corrosion

Exposure for twenty-eight days to the atmosphere in the industrial district of Attercliffe, Sheffield.

The specimens were previously heated to 750° C. and cooled in air.

Hadfield Group Research Number.	Analysis. C. %	Mn. %	Special Element %	Fe. %	Brinell Hardness Number.	Loss in Weight in Grams per 100 Sq. Cms.	Nature of the Corrosion.
PLATINUM STEELS.			Pt.				
43 E.1-3	1·20	—	1·05	97·80	246	0·66	A small area in the centre of the underlying face was still bright. Rust rather more easily removed than from 31/D.4 and surface more coarsely pitted.
31 D.4	0·07	—	2·25	97·70	158/170	0·49	Underlying face completely covered with rust. Rust fairly difficult to remove. Surface very finely pitted.
17 C.1-6	0·61	—	2·50	96·70	280	0·66	Underlying face rusted over. Rust easily removed. Surface very finely pitted.
RHODIUM STEEL.			Rh.				
25 C.3-1	0·97	—	1·60	97·50	278	0·66	Under surface completely rusted over. Rust easily removed and surface very finely pitted.
CARBON STEEL.							
50 E.2-2	1·52	—	—	98·16	232	1·22	Underlying face rusted over. Rust fairly difficult to remove. Surface more coarsely pitted than that of 25/C.3-1.
MODERN STEELS, As Forged (for comparison)							
"Ingot Iron"	0·03	0·08	—	—	89	1·04	Small area about ¼ in. square of underside bright, though marked with specks of rust. Not difficult to clean. Pitted not quite so coarsely as 50/E. 2-2.
Mild Steel .	0·11	0·39	—	—	114	1·16	Similar to "Ingot Iron."

Since physical condition plays a part in corrosion problems, all the specimens were first heat treated alike, being heated to 750° C. for fifteen minutes and cooled in air. The surfaces were cleaned of scale and polished, the pieces measured, dried in an air oven and weighed.

The exposure of the specimens was for twenty-eight days on the roof of the Hecla Works, Attercliffe, Sheffield, where experience has shown that the conditions are particularly severe due to the nature of the atmosphere in this district devoted to the manufacture of iron and steel.

At the end of this period the rust was removed by gentle rubbing with a soap of the type incorporating a hard powder, and the pieces were washed, dried and again weighed.

Table X., in which the results are given, displays the interesting fact that both platinum and rhodium additions to steel, and specially the latter metal, in the amounts to which they are present appreciably retard corrosion. This improvement, however, does not appear to be of striking practical value. That is, while it is possible that under ordinary conditions the tarnishing or rusting of instruments or mirrors made from these alloys might take somewhat longer than with carbon steels, the desired object was not fully attained. Nevertheless, these results do suggest a possibility that with appreciably larger percentages of platinum, and particularly rhodium, alloys having distinct claims to non-corrodibility might be obtained, specially, too, when it is remembered that it is only in the comparatively high percentages of 12 per cent. and over that chromium steels acquire a usefully non-corrodible character.

(*f*) *Specific Magnetism.*—In examining the magnetic character of the specimens, the simple form of test devised by the author, and described in the joint paper by Professor H. K. Onnes, Dr. H. R. Woltjer and himself, "On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese," read before the Royal Society in March, 1921, proved useful. This test, which determines the specific magnetism of the specimen as compared with pure iron, requires specimens of uniform size and shape, but with certain adaptations could be applied to several of the specimens, and although the necessary modifications detracted somewhat from the accuracy obtainable, it was nevertheless thought useful to take advantage of the method in this limited way.

So far as standards of known specific magnetism could be prepared similar in form to any of the Faraday specimens, a necessary qualification of which also was that they should possess one flat surface, these specimens could be tested as a whole without cutting

them up. The uniformly shaped specimens of the E group naturally proved the most convenient.

Table XI. records the results of these tests, the approximate character of which should be recognised, as also the indefinite condition as regards heat treatment of most of the specimens. It

Table XI

Specific Magnetism of the Specimens in the condition as Received by the Author.

Hadfield Research Number.	Group Number.	Analysis.				Specific Gravity.	Specific Magnetism.
		C. %	%	Pt. %	Fe. %		
41	E. 1–1	1·12	—	0·90	97·50	—	91
42	E. 1–2	—	—	—	—	7·82	93
43	E. 1–3	1·20	—	1·05	97·80	—	98
44	E. 1–4	—	—	—	—	7·79	90
45	E. 1–5	—	—	—	—	7·80	100
46	E. 1–6	0·94	—	1·15	97·60	7·84	100
47	E. 1–7	1·30	—	1·10	97·30	—	91·5
48	E. 1–8	—	—	—	—	7·84	96·5
49	E. 2–1	—	—	—	—	7·78	96·5
50	E. 2–2	1·52	—	—	98·16	—	91
51	E. 2–3	—	—	—	—	7·79	95
52	E. 2–4	—	—	—	—	7·70	94
53	E. 2–5	1·50	—	—	98·40	—	90
54	E. 2–6	1·47	—	—	98·30	7·80	92
55	E. 2–7	—	—	—	—	7·80	98·5
56	E. 2–8	1·48	—	—	98·27	—	96
			S.	P.			
57	E. 2–9	0·12	0·027	0·124	99·65	—	100
58	E. 2–10	0·07	—	0·128	99·20	—	100
59	E. 2–11	1·45	—	—	98·20	—	100
			Ag.				
60	E. 3–1	1·22	0·20	—	98·10	—	94
				Pt.			
61	E. 3–2	1·35	—	0·80	97·65	—	98
62	E. 3–3	1·05	—	1·40	97·34	—	95

may be remarked, however, that the fact that none of the specimens contains any large proportion of an alloying element is reflected in the generally high figures obtained for the specific magnetism, platinum, apparently, not causing any pronounced lowering of the figure.

(*g*) *Forging Properties.*—For the examination so far made it was possible to utilise the specimens as a whole, or small pieces cut

from them. There remained, however, certain desirable kinds of test requiring special forms of test-pieces which, owing to their shape or relatively large size, could not, except in an extravagant way, be obtained in this manner.

In these circumstances recourse was made to forging down a sufficient portion of some of the specimens for this purpose. This again required special consideration for the following reasons. The practically complete absence of manganese did not promise well for the forging properties. It is true most of the specimens in the collection had actually been forged. Many of them, however, showed imperfections, and although these could often be removed before further forging, the material was apparently not very suitable to produce test-pieces of the soundness required.

For these further tests, therefore, the selection of available specimens was limited. Those actually forged were as follows, and at the same time a brief record of their behaviour is presented. It was planned where possible to prepare a specimen 65 mm. in length for examination in the Chevenard Differential Dilatometer; from a portion of this a tensile test-piece could be obtained suitable for the tensometer apparatus.

Specimen No. 14/*C*.1-3 (*C* 0·94, *Pt* 0·74).—Preparatory to forging, any surface imperfections were removed by filing.

Forging commenced at 850/950° and finished by swaging at a black heat. A length of $8\frac{1}{2}$ inches of $\frac{3}{16}$-inch-square section was thus prepared, three heatings being required. The material forged easily and well in this operation.

A length suitable for the dilatometer and a piece $\frac{1}{2}$ inch long for micro examination were cut off, and the remaining $5\frac{1}{2}$ inches examined for defects, which were removed.

After reheating to 850° the piece was then further forged by flattening and edging down to about 0·07 × 0·25 inch. A burst about $\frac{1}{2}$ inch long then appeared in the middle of one of the narrow edges. Further forging was therefore confined to the material on each side of the defect, which was flattened down to 0·027 inch in thickness.

The strip thus obtained was from 0·40 to 0·62 inch in width, and had a Brinell hardness of 340/360. To remove possible strains which might cause splitting in cutting up the strip, it was reheated to 775° and cooled slowly, its hardness then being 190.

By parting the strip down the centre, four pieces, 0·027 × 0·20 inch, were obtained of a total length of 19 inches. These strips were, as explained later, used in making the blades of some miniature knives, one of which is shown in Plate XLVIII.

The Chevenard test-piece, when it had served the purpose of the test, was further forged so as to prepare from it a tensometer tensile test-piece. The sounder end of the piece was heated to 850° and upset by forging to 0·25 inch diameter. This portion was then cut off to a length of $1\frac{1}{4}$ inch and similarly upset at its other end, from which a tensometer test-piece $1\frac{1}{16}$ inch in length was machined.

The remainder of the Chevenard test-piece was forged into strip and cut up into the small knife blade section providing, with difficulty, two pieces 3 inches in length, the material in this case tending to crack in forging on the edges and ends.

Specimen No. 15/*C*.1-4 (*C* 0·94, *Pt* 0·69).—The forging of this specimen was with the intention of preparing from it, if possible, a razor blade of ordinary size, which could be tested in a practical way. As the whole of the specimen was necessary for this purpose it precluded in this case any other test-pieces being obtained.

The specimen was $\frac{3}{4} \times \frac{7}{16}$ inch in section, tapered down at one end to $\frac{1}{4} \times \frac{1}{2}$ inch, there being a drill hole in this tapered end. At the wider end there was a V-shaped groove.

On commencing forging at about 850° the V-shaped groove opened out slightly, disclosing a seam. A small piece was therefore sawn off this end as far as the crack appeared to go. The narrow and drilled end of the specimen was also cut off and appeared sound.

The piece was then reheated to about 850° and forged down on the anvil, a few cracks developing on getting down close to the V section suitable for a razor blank.

Finally, a bar 0·46 to 0·55 inch wide, 0·20 to 0·23 inch in thickness on one edge and 0·04 inch on the other, was obtained $6\frac{1}{4}$ inches in length, containing, however, some slight imperfections.

Specimen No. 17/*C*.1-6 (*C* 0·61, *Pt* 2·50).—Micro examination of this specimen, as previously explained, had revealed decarburisation to a depth of about $1\frac{1}{4}$ mm. confirmed by hardness determinations. After removing all this decarbonised material and any forging seams penetrating below it, the section remaining was very small, 0·35 × 0·25 inch. For reasons of economy of material it was therefore decided to abandon in this case the idea of a Chevenard test, and prepare only a tensometer specimen and the material necessary for obtaining a heating and cooling curve of the inverse rate type, which could be carried out on a piece of very small dimensions.

A piece 0·55 inch long of the reduced section and weighing 6·5 grams, was therefore cut off and forged gently at a commencing

temperature of 900/950° C. down to 0·25 inch diameter. The piece obtained was $1\frac{1}{4}$ inch long, but showed a bad transverse burst $\frac{1}{4}$ inch from one end. This was sawn off and used for the heating and cooling curve, the remainder, 1 inch in length, being allocated for the tensometer test-piece. In this forged condition the Brinell hardness was 265.

Specimen No. 29/*D*.2 (*C* 1·05, *Cu* 2·79).—A piece 0·8 to 0·9 inch in length had been fractured from this specimen, and was therefore made use of for a forging test.

The Brinell hardness of the piece was variable from 390 to 710, and as a precautionary measure it was therefore softened by heating to 650° and cooling in air, the hardness then being 330. Seams on the faces and edges were filed and gouged out and the edges rounded off.

Forging was commenced at 850/900°, and while the material behaved at first satisfactorily, in finishing to 0·22 inch diameter both ends commenced to open, one rather badly. The length was just in excess of the 65 mm. required for a Chevenard test, and it was hoped that although imperfect the specimen would serve for this purpose. As will be seen later, a curve was successfully obtained from it.

Specimen No. 9/*B*.6 (*C* 0·92, *Rh* 1·20).—To have as complete a series of tests as possible on one of the steels containing rhodium seemed specially desirable. These steels were only three in number. No. 25/C.3-1 contained the highest percentage, 1·60, and was too small in size to obtain more tests than had already been taken. Of the two remaining specimens, Nos. 7/B.4 and 9/B.6, there was not much to choose on the score of soundness, but B.6 had the higher rhodium content and was therefore chosen.

Since unsoundness at the centre of this specimen was visible at the drill hole, and there were external surface roaks, these defects were avoided by sawing out a piece from the material between the centre and the outside so as to obtain a specimen as sound as possible for forging. When filed up on all faces and all visible defects gouged out, this piece weighed 18·6 grams, its size being 0·55 × 0·36 × 0·85 inch.

Forging commenced at the temperature of 850/900°, four re-heatings being required in reducing to 0·25 inch square. On the finished piece there were many small cracks, some apparently superficial, others going in for a depth of $\frac{1}{16}$ inch. The piece when squared at the ends to a length of 65 mm. was found suitable for a Chevenard test. As forged the Brinell hardness was 255.

Specimen No. 22/*C*.2-2 (*C* 1·06, *Ni* 2·18, *Au* 0·75).—The section

of this specimen, 13 × 4 mm., being rather flat was not well suited to forging into a small round or square bar, but in view of its interesting composition an attempt was made as follows :—

Some defects visible on the corners over a length of 1½ inches were removed by filing and gouging.

The piece was forged with light blows at a commencing temperature of 800° to a square section, during which operation the material appeared sound. After reheating, the corners were rounded and with a further reheating the piece was put through ¼-inch diameter swages, but it was not found possible to prepare either a tensometer specimen or a dilatometer test-piece of satisfactory character, the material splitting away.

The best that could be done, therefore, was to cut a piece ⅛ inch long from what was left of the forged ¼-inch-round section, from which to obtain a heating and cooling curve of the inverse rate type. A tensometer test-piece was obtained from this specimen in another way, as will be found recorded in the section on tensile tests.

Specimen No. 57/*E*.2-9 (*C* 0·12, *S* 0·027, *P* 0·124, *Fe* 99·65).—In the forging of this specimen no difficulty was experienced.

The piece was rounded gently under the hammer at a commencing temperature of 1100° C., then reheated and swaged to ¼ inch diameter. With further reheating swaging continued down to 5/32 inch diameter, a length being obtained of 68 mm. suitable for a Chevenard specimen.

General Comments regarding the Forging Properties.—It may be remarked that the steels containing platinum and rhodium appear to be quite readily forgeable, such difficulties as were met with being due to imperfections in the original specimens.

No. 29/D.2, however, containing 2·79 per cent. copper, seems to be a steel which is difficult to forge successfully, this being in accordance with the author's own experience with high-percentage copper steel. On the other hand, steels with comparatively low percentages of copper can be forged and rolled without difficulty, but upon exceeding about 5 per cent. of copper such steels may be regarded as unsuitable for forging.

It is somewhat difficult to decide as to the merits, from the point of view of forging, of such a composition as that represented by Specimen No. 22/C.2-2 (Ni 2·18 and Au 0·75). Starting with a material of a section and condition unsuitable for the forging operations proposed, it would in any case have been difficult to guarantee satisfactory behaviour of the material even if of known good forging properties. The author is inclined, however, as the result

of this experience, to believe that steel of this composition has not very good forging properties, but it must be remembered there is only 0·10 per cent. of manganese present.

(*h*) *Determination of Critical Temperature Ranges.*—(i.) *Dilatometric Method.*—Because of the more complete indications it gives of internal thermal changes than those provided by the usual heating and cooling curves indicating the evolution or absorption of heat, the dilatometric method was preferred and adopted wherever it was possible to obtain a suitable specimen. Nevertheless, where only the smaller specimen suitable for the inverse rate method could be obtained, the information obtainable by this method was accepted as an alternative.

For the dilatometric method the excellent apparatus used was the differential mechanical dilatometer devised by M. Pierre Chevenard and described by him in his article, "Dilatomètre Differéntiel a Enregistrement Mécanique," published in the *Revue de Métallurgie*, 23^{e} année, No. 2 (February 1926, pp. 92 to 99). Test-pieces from the Faraday specimens had been provided by forging from Nos. 9/B.6, 14/C.1-3, 29/D.2 and 57/E.2-9. Since the first three of these are alloy steels, comparison test-pieces were provided of plain carbon steel low in manganese, of modern manufacture and closely similar carbon content.

The procedure adopted was of a uniform kind, heating and cooling being controlled by a water rheostat operating on the heating furnace, at a fairly constant rate of 5 to 7 secs. per ° C. The maximum temperature was 950° C. The first heating was from the as forged condition, and in all cases concordant results were obtained from a repetition heating made as a check.

The curves from specimens 14/C.1-3 (C 0·94, Pt 0·74), 9/B.6 (C 0·92, Rh 1·20) and 1991/2 (C 0·97) are reproduced as examples in Figs. 2, 3 and 4, the critical ranges observed in all the specimens being shown in Table XII.

Rhodium to the amount of 1·20 per cent., as shown by these results, has practically no influence on the critical temperature ranges of 0·9 per cent. carbon steel; 0·74 per cent. platinum, on the other hand, has lowered the critical ranges by about 30°. In addition, the actual ranges of temperature covered by the transformations show a tendency to extend, and the curves at the commencement of the critical ranges are rather more rounded, indicating that due to the introduction of platinum there is a certain sluggishness in the transformations.

Copper to the amount of 2·79 per cent. in Specimen 29/D. also lowers the critical ranges under these conditions by about 20° C.

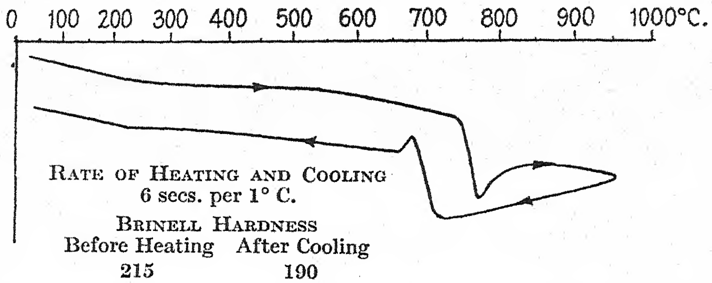


FIG. 2.—Heating and Cooling Curves obtained in the Chevenard Dilatometer for Faraday Steel Specimen 9/B6.

	C.	Si.	Mn.	Ni + Cu.	Rh.	Fe.	
Analysis :	0·92	0·33	Trace	0·07	1·20	97·35	forged material.

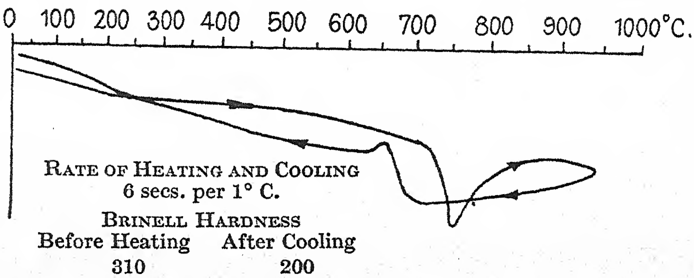


FIG. 3.—Heating and Cooling Curves obtained in the Chevenard Dilatometer for Faraday Steel Specimen 14/C1–3.

	C.	Si.	Mn.	Fe.	Pt.	
Analysis :	0·94	0·33	Nil	97·60	0·74	forged material.

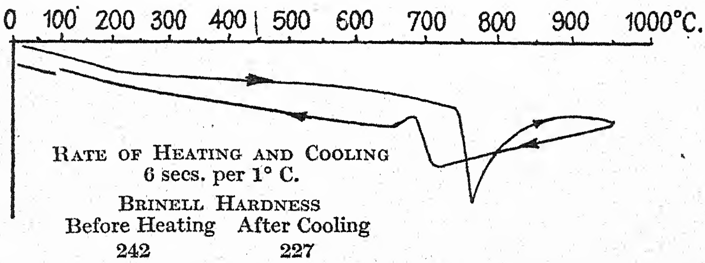


FIG. 4.—Heating and Cooling Curves obtained in the Chevenard Dilatometer for a Specimen of Modern Carbon Steel 1991/2.

	C.	Si.	S.	P.	Mn.	
Analysis :	0·97	0·13	·032	·032	0·12	forged material.

on heating and 40° on cooling, again introducing some sluggishness into the transformations.

As regards Specimen No. 57/E.2-9 the curve obtained and the temperatures indicated for the critical ranges are characteristic of those usually obtained for wrought iron.

Table XII

Critical Temperature Ranges of Steels made by Faraday as shown by the Chevenard Differential Dilatometer: also Plain Carbon Steels of similar carbon content for Comparison.

The rate of Heating and Cooling was uniform at 5 to 7 secs. per ° C., thus requiring $1\frac{3}{4}$ hours to reach the maximum temperature of 950° C., and 1 hour to fall to 400° C.

Hadfield Research Number.	Group Number.	Analysis.						Critical Temperature Ranges.					
								Heating.			Cooling.		
		C.	Si.	Mn.	Special Element.		Fe.	$Ac_{3,2,1}$			$Ar_{3,2,1}$		
		%	%	%	%	%	%	Commt.	End.	Range.	Commt.	End.	Range.
					WROUGHT IRON.								
57	E.2-9	0·12		Tr.	S. ·027	P. ·124	99·65	$Ac_2$775 $Ac_3$915	— 945	— 30°	$Ar_2$775 $Ar_3$910	— 885	— 25°
					COPPER STEEL.								
29	D.2	1·05			Cu. 2·79		96·30	735	755	20°	695	665	30°
					PLATINUM STEEL.								
14	C.1-3	0·94	0·33		Pt. 0·74		97·60	715	745	30°	700	655	45°
					RHODIUM STEEL.								
9	B.6	0·92	0·33	Tr.	Rh. 1·14 1·20		97·35	745	770	25°	715	680	35°
					MODERN CARBON STEELS (FOR COMPARISON)								
1991/2		0·97	0·13	0·12				750	770	20°	720	695	25°
1584C/2		1·06	0·13	0·05				755	775	20°	730	705	25°

The cementite change was observed uniformly at 210/220°, both on heating and cooling in all the high carbon steels, whether plain or alloyed.

(ii.) *Inverse Rate Curves.*—For taking heating and cooling curves of the inverse rate type the specimens available were 17/C.1-6 and 22/C.2-2. No. 14/C.1-3 was also included for comparison with the

Chevenard curves on this specimen. The test specimen in these cases was very small, only about $\frac{1}{4}$ inch round or square and $\frac{3}{8}$ inch

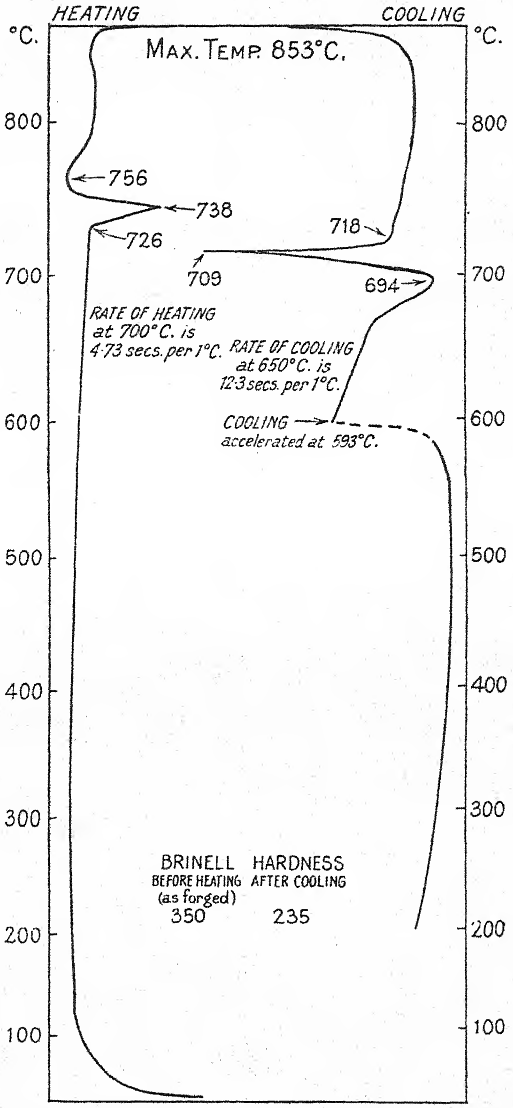


Fig. 5.—Heating and Cooling Curves of the Inverse Rate Type for Faraday Steel Specimen 14/C.1–3.

	C.	Si.	Mn.	Fe.	Pt.	
Analysis :	0·94	0·33	Nil	97·60	0·74	forged material.

long, weighing 2 to 3 grams, and a hole was drilled most of the way down the axis to receive the platinum, platinum-rhodium thermo-

couple. As with the dilatometric examination comparison pieces were provided of carbon steel low in manganese.

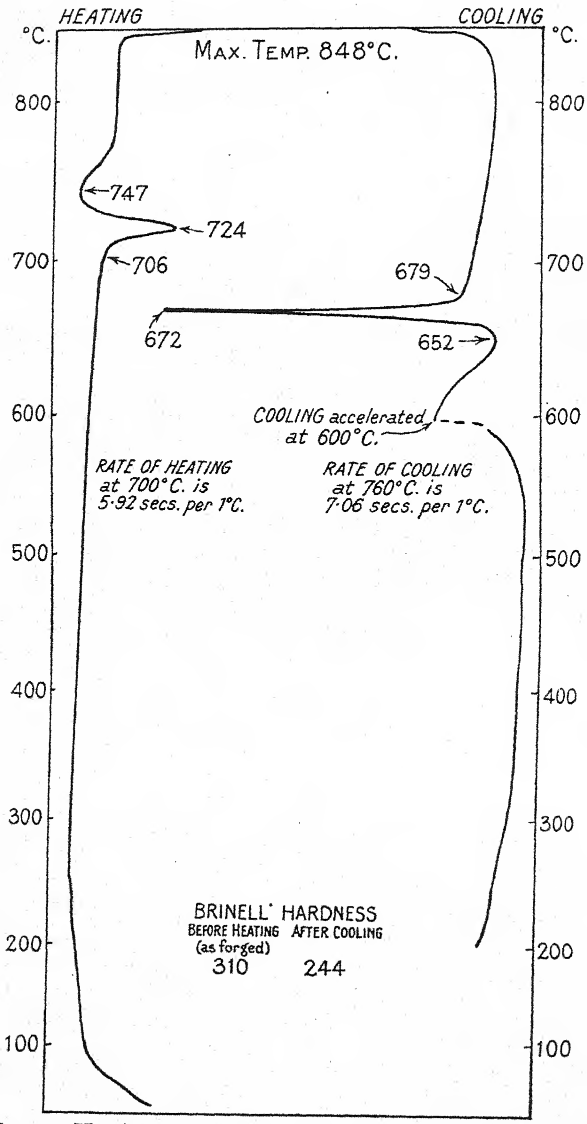


FIG. 6.—Heating and Cooling Curves of the Inverse Rate Type for Faraday Steel Specimen 22/C.2–2.

	C.	Si.	Ni.	Cu.	Au.	Fe.	
Analysis :	1·06	0·08	2·18	0·03	0·75	96·00	forged material.

Uniform conditions of heating and cooling were adopted, the specimens reaching their maximum temperature of 850° C. in one

hour, and cooling to about 600° in a further forty minutes. After this, the transformations being completed, the rate of cooling was

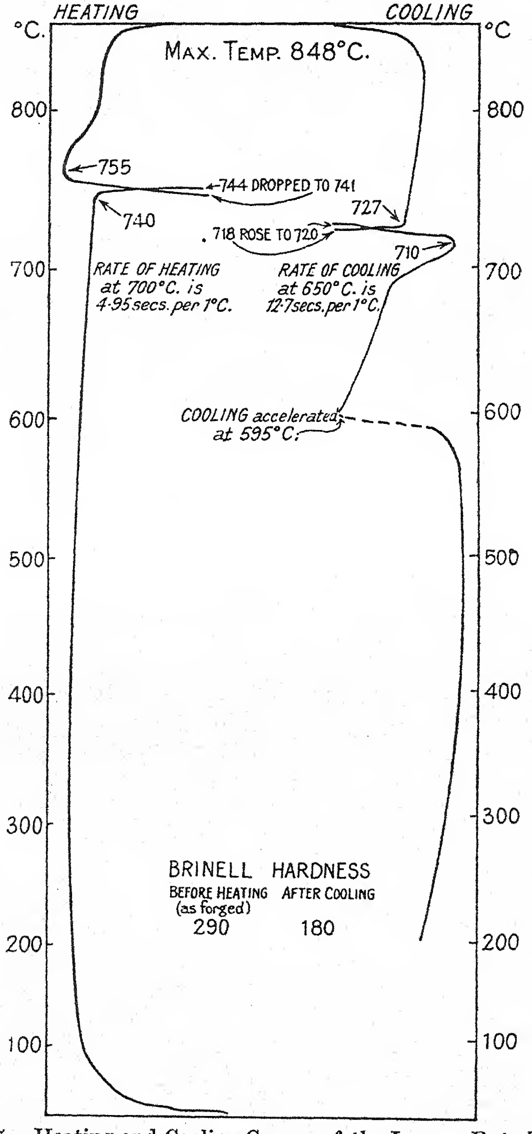


FIG. 7.—Heating and Cooling Curves of the Inverse Rate Type for a Specimen of Modern Carbon Steel 1991/2.

	C.	Si.	S.	P.	Mn.	
Analysis :	0·97	0·13	·032	·032	0·12	forged material.

accelerated. Observations were taken in the usual way on a delicate reflecting pyrometer using a millimetre scale and recording

the transits across each millimetre by chronograph. The diagrams for 14/C.1-3 (C 0·94, Pt 0·74) and 22/C.2-2 and 1991/2 are reproduced in Figs. 5, 6 and 7, Table XIII. recording the full data as to the transformation. The specimens were heated initially from

Table XIII

Critical Temperature Ranges of Steels made by Faraday as shown by Heating and Cooling Curves of the Inverse Rate Type; also plain Carbon Steels of similar carbon content for Comparison

The specimens were heated to a maximum temperature of 850° C. in one hour, and cooled to about 600° C. in forty minutes, the rate of cooling after this being accelerated.

Hadfield Research Number.	Group Number.	Analysis.						Critical Temperature Ranges.					
								Heating.			Cooling.		
								Ac.$_{3,2,1}$.			Ar$_{3,2,1}$.		
		C. %	Si. %	Mn. %	Special Element. %	%	Fe. %	Comm.	Max.	End.	Comm.	Max.	End.
					Platinum Steels.								
14	C.1-3	0·94	0·33		Pt. 0·74		97·60	726	738	756	718	709	694
17	C.1-6	0·61	0·05		2·50		96·70	723	731	752	700	691	674
					Nickel-Gold Steel.								
22	C.2-2	1·06	0·08		Ni. 2·18	Au. 0·75	96·00	706	724	747	679	672	652
					Modern Carbon Steels (for comparison).								
1991/2		0·97	0·13	0·12				740	*741–744	755	727	*718–720	710
1584C/2		1·06	0·13	0·05				741	*742–744	757	727	*722–726	717

* Indicates decalescence on heating or recalescence on cooling.

their condition as forged, and in each case a repetition heating provided a satisfactory check.

Since the test-piece from No. 17/C.1-6 was prepared from its centre portion, the results in this case should properly be compared with those from 1991/2 or 1584C/2, and not with a 0·60 per

cent. carbon steel. The low figure of 0·61 per cent. carbon obtained in the analysis of this specimen is, it will be remembered, accounted for by the drillings containing some of the decarburised surface material. The carbon in the centre unaltered portion was not separately determined, but micro examination shows it to be certainly over 0·90 per cent. Above this percentage there is, as the data show, little change in the character of the heating and cooling curves of carbon steel; consequently either 1991/2 with 0·97 per cent. carbon or 1584C/2 with 1·05 per cent. carbon will in these cases serve for comparison.

Some lowering of the critical changes due to the addition of platinum is shown by the data for 14/C.1-3 with 0·74 per cent. platinum, confirming the information obtained from the Chevenard curves, although in not quite so marked a way. The sluggishness introduced by the platinum as compared with plain carbon steel also extends here to the temperature range over which the transformations occur.

The same features are observed to a more marked degree in Specimen 17/C.1-6 with higher platinum content, 2·50 per cent., the critical ranges being lowered in temperature by 20° to 30°, and further widened in their extent.

In Specimen 22/C.2-2, containing nickel 2·18 per cent. and gold 0·75 per cent., the critical ranges are lowered by about 40°, and widened by about 20° as compared with plain carbon steel; both these effects are about what might be expected from the nickel addition alone, so that there is apparently no material effect due to the gold itself.

(*k*) *Thermal Expansion.*—The dilatometric method of determining critical temperature ranges has the special and supplementary advantage that it provides at the same time information as to the coefficient of thermal expansion over the temperature explored. These coefficients were therefore ascertained from the Chevenard curves obtained from the various specimens tested. Those concerned are 29/D.2 (2·79 per cent. Cu), 14/C.1-3 (0·74 per cent. Pt), 9/B.6 (1·20, 1·14 Rh), with the carbon steels 1991/2 (0·97 per cent. C) and 1584C/2 (1·05 per cent. C). In addition, the wrought-iron specimen 57/E.2-9 and the wrought iron used for comparison, numbered 4906. For the high carbon steels, whether plain or alloyed, there is a remarkable uniformity in the results. These can all be expressed within close limits by the following figures, representing the coefficient of expansion in millionths per ° C.: at ordinary temperature 11·0, 100°–11·5, 300°–14·0, 500°–16·5, and at 700° C.–16·0.

In the case of 29/D.2, where the percentage of the added element is much higher than in the other two, an exception should possibly be made, its coefficients being better represented by adding 0·5 to each of the above figures. It may be concluded, therefore, that the coefficient of expansion of carbon steel is not materially influenced by the addition of comparatively small percentages of either copper, platinum or rhodium. In the case of the two wrought-iron specimens, these give figures identical with each other, but differing slightly from those of the high carbon steels above mentioned, the

Table XIV

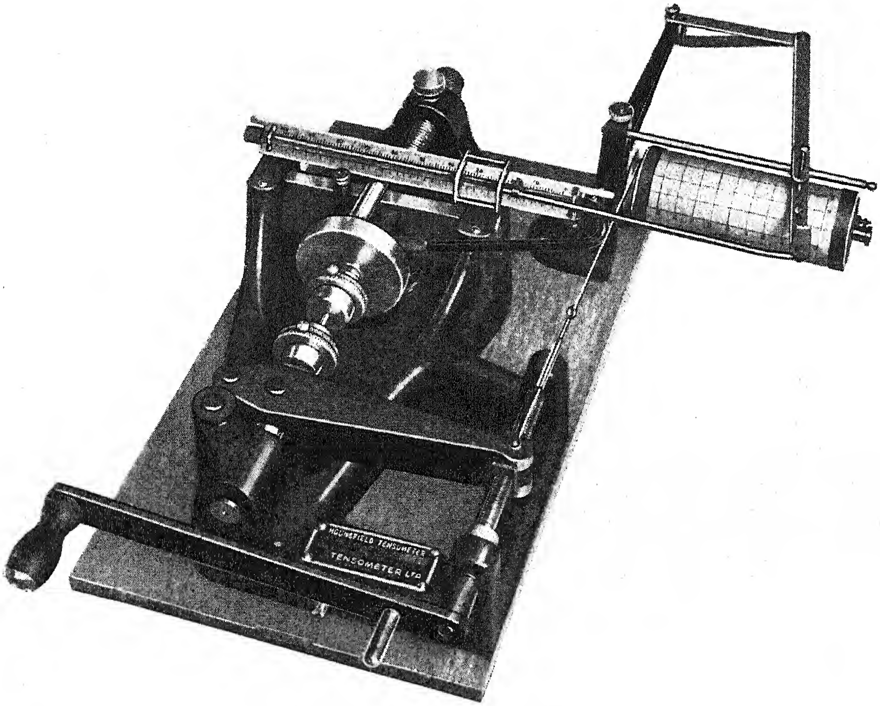
Specific Electrical Resistance

Test specimens slowly cooled from 950° C.

Hadfield Research Number.	Group Number.	Analysis. C. %	Si. %	Mn. %	Special Element. %	%	Fe. %	Temp. of Test.	Specific Electrical Resistance. Microhms per c.c.
Wrought Iron.									
57	E. 2–9	0·12	—	trace	S. ·027	P. ·124	99·65	18°	11·9
Platinum Steel.									
14	C. 1–3	0·94	0·33	—	Pt. ·74	—	97·60	20°	20·0
Rhodium Steel.									
9	B. 6	0·92	0·33	trace	Rh. {1·20, 1·14}	—	97·35	18°	19·7
Wrought Iron and Modern Carbon Steels. (for comparison)									
4906		0·02	0·14	trace	S. 0·013	P. 0·013	—	18°	12·1
1991/2		0·97	0·13	0·12	S. 0·032	P. 0·032	—	23°	19·2

figures being at ordinary temperature 12·0, at 100°–12·5, at 300°–14·0, 500°–16·0 and at 700°–15½.

(*l*) *Electrical Resistance.*—It was possible to make upon the Chevenard test-pieces a test of their specific electrical resistance, and although such a test is necessarily approximate owing to the small size of the specimen, since little is known about the effect of such elements as platinum and rhodium upon steel in this connection, it was thought worth while. In these tests, Specimen No. 29/D.2 was necessarily excluded, because although its seaminess did not prevent a successful Chevenard examination being made, this unsoundness would undoubtedly have a considerable effect on the electrical resistance.



THE HOUNSFIELD TENSOMETER.

[*To face p.* 204.

The usual fall of potential method was employed, a steady current being passed through the specimen, through copper leads attached at the ends and through a standard manganin resistance. The fall of potential over this resistance, and, by means of bronze knife edges, over a measured length of the specimen well clear of the ends, was determined on a potentiometer. These measurements, in conjunction with the sectional dimensions of the specimens, enable the specific resistance to be calculated, Table No. XIV. giving the figures obtained.

The addition of platinum and rhodium clearly has very little effect upon the electrical resistance of carbon steel. Such a result is not altogether surprising, being in accordance with the general rule that the elements having the largest atomic volumes have the greatest effect. Platinum and rhodium have small atomic volumes.

The figure obtained for Specimen No. 57/E.2-9 shows that its electrical resistance is of the same order as normally found for wrought iron.

(*m*) *Tensile Tests.*—The much improved facilities for metallurgical examination which we now possess, as compared with those available to Faraday, are well illustrated by the tensile tests which the author has been enabled to carry out on some of the specimens notwithstanding their small dimensions. With the ingenious little apparatus shown in Plate XLVII., known as the Tensometer, designed by Mr. L. H. Hounsfield, M.I.Mech.E., tests can be carried out and full tensile data obtained from a specimen of the very small dimensions shown in the sketch, Fig. 8, and weighing (in steel) less than 4 grams. By means of an autographic attachment a stress-strain diagram up to the point of fracture can be obtained.

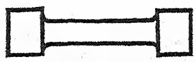


FIG. 8.—Sketch of Tensometer Test-piece (full size).

By forging, pieces suitable as blanks for tensometer test-pieces had been obtained from Specimens Nos. 9/B.6, 14/C.1-3 and 17/C.1-6, the first two being prepared from a portion of the Chevenard dilatometer test-piece. In the case of No. 22/C.2-2, as there appeared to be sufficient thickness in the unforged portion of the specimen, a piece $1\frac{1}{4}$ inch long by $\frac{1}{4}$ inch wide was sawn out from the middle, thus leaving its contour undisturbed. This, however, did not provide a completely satisfactory specimen, blemishes remaining on the surface of the finished test-piece where a depression in the surface of the original specimen had not been completely removed by machining.

Similar test-pieces were, for purposes of comparison, prepared

from the high carbon steels of modern manufacture previously made use of in connection with the examination of the critical ranges. To render all results directly comparative the test-piece

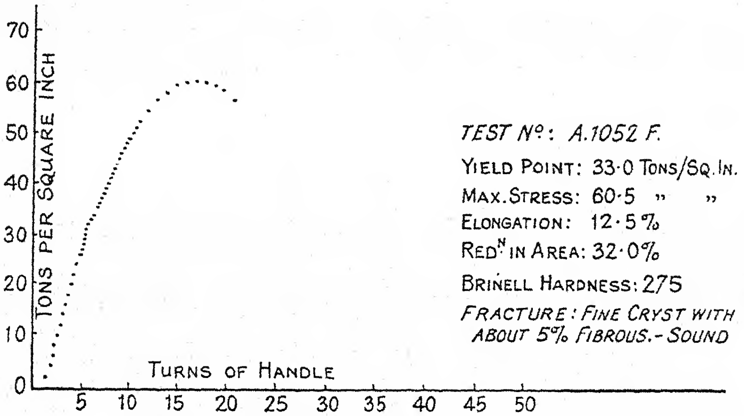


FIG. 9.—Autographic Tensile Stress Strain Diagram obtained on the Hounsfield Tensometer from Faraday Steel Specimen 14/C 1–3.

	C.	Si.	Mn.	Fe.	Pt.
Analysis :	0·94	0·33	Nil	97·60	0·74

Heat treatment : Cooled in AIR from 800° C.

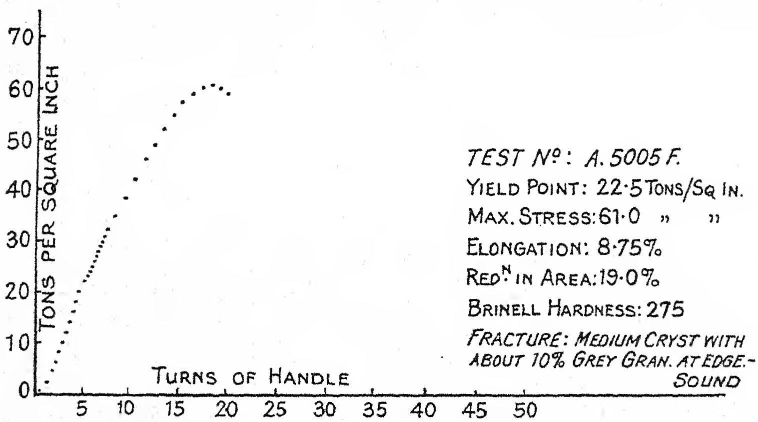


FIG. 10.—Autographic Tensile Stress Strain Diagram obtained on the Hounsfield Tensometer from Faraday Steel Specimen 9/B6.

	C.	Si.	Mn.	Rh.	Fe.
Analysis :	0·92	0·33	Trace	1·14 1·20	97·35

Heat treatment : Cooled in AIR from 800° C.

blanks were in every case normalised before machining to pattern, by heating them to 800° C. and cooling in air.

Examples of the stress-strain diagrams obtained are reproduced

in Figs. 9, 10 and 11, and the test data as a whole are recorded in Table XV.

As compared with the high carbon steel 1991/2 of similar carbon content, Specimen No. 14/C.1-3 with 0·74 per cent. platinum, it will be seen, has a somewhat high tenacity (60·5 tons per square inch as compared with 58·0 tons). Its yield point is also higher, 33 tons against 29. At the same time, the elongation and reduction of area are precisely the same as that of the carbon steel. Platinum to this amount, 0·74 per cent., therefore, as shown by this test, effects a slight but distinct improvement in the tensile properties of high carbon steel. Had sufficient material been available it

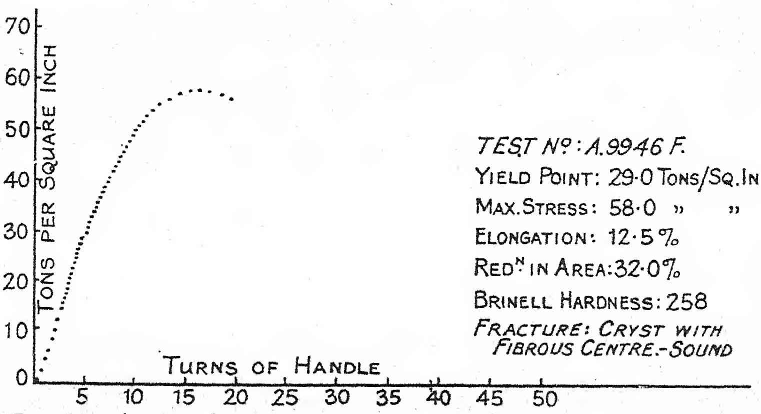


FIG. 11.—Autographic Tensile Stress Strain Diagram obtained on the Hounsfield Tensometer from a Specimen of Modern Carbon Steel 1991/2.

	C.	Si.	S.	P.	Mn.
Analysis :	0·97	0·13	·032	·032	0·12

Heat treatment : Cooled in AIR from 800° C.

would have been particularly interesting to test this point further on specimens which had been quenched and tempered.

The specimen from No. 17/C.1-6 (2·50 per cent. Pt) unfortunately broke prematurely at a load of 38·5 tons per square inch, and when the elongation had only reached 1·25 per cent. This was clearly traceable to a defect visible in its fracture. It will be remembered that special difficulty had been experienced in the preparation of this test-piece, and although an apparently sound portion had been cut for the purpose from the rather defective forging obtained, it was evidently not so sound as it appeared.

In order to give some idea of the thoroughness with which Faraday worked, Table XVI. has been prepared, and in this the steels are arranged in the order of gradually increasing percentages of platinum. The various platinum steels produced by him and of

TABLE XV

Tensile Tests

On specimens 0·159 in. diam. in the Tensometer Testing Machine.
Material previously cooled in air from 800° C.

Hadfield Research Number.	Group Number.	Analysis.						Tensile Test.					Brinell Hardness Number.
		C. %	Si. %	Mn. %	Special Element. %	%	Fe. %	Yield Point.	Max. Stress.	Elongation.	Reduction of Area.	Fracture.	
								Tons 1 sq. in.		Per cent.			
PLATINUM STEELS.													
14	C.1-3	0·94	0·33		Pt. 0·74		97·60	33	60·5	12·5	32	Fine cryst. with about 5 per cent. fibrous.	275
17	C.1-6	0·61	0·05		2·50		96·70	37	38·5	1·25	1·50	Fine cryst. Defective.	275
RHODIUM STEEL.													
9	B.6	0·92	0·33	Tr.	Rh. 1·14 1·20		97·35	22·5	61·0	8·75	19·0	Medium cryst. with about 10 per cent. grey gran. Sound.	275
NICKEL-GOLD STEEL.													
22	C.2-2	1·06	0·08		Ni. 2·18	Au. 0·75	96·00	40	54·5	2·5	3·0	Fine grey gran. Sound. Testpiece fractured at a surface blemish.	300
MODERN CARBON STEELS (FOR COMPARISON).													
1991/2		0·97	0·13	0·12				29	58·0	12·5	32	Cryst. Fibrous centre.	258
1584C/2		1·06	0·13	3·05				28·5		13·75	33	Granular.	235

which the analyses presented have been made for this research by the author are thus brought together in one group. There are in all twenty-three separate specimens, varying from 0·68 to 48·60 per cent. Pt. These complete the series with the exception

Table XVI

Platinum Steels made by Faraday, arranged approximately in Divisions according to the Increasing Percentage of Platinum present.

The various Steels from which the Analyses are made form part of the 90 Specimens dealt with by the author in this Research.

Division.	Hadfield Research Number.	Group Mark.	Analysis, per cent.			
			C.	Pt.	Fe.	
A	18	C. 1-7	0·84	0·68	97·90	
	15	C. 1-4	0·94	0·69	98·30	
	3	A. 3	0·92	0·73	97·90	
	5	B. 2	0·92	0·73	97·90	
	14	C. 1-3	0·94	0·74	97·60	
	21	C. 2-1	0·94	0·75	97·90	
	2	A. 2	0·69	0·80	98·25	
	61	E. 3-2	1·33	0·80	97·65	
B	41	E. 1-1	1·12	0·90	97·50	
	43	E. 1-3	1·20	1·05	97·80	
	47	E. 1-7	1·30	1·10	97·30	
	T B	W R	0·84	1·10	97·80	Faraday - Stodart - Indian Wootz-Barnard Razor.
C	46	E. 1-6	0·94	1·15	97·60	
	10	B. 7	0·86	1·20	97·34	
D	8	B. 5	1·03	1·34	96·80	This alloy also contained 0·31 per cent. Ag.
	62	E. 3-3	1·05	1·40	97·45	
	39B	D. 12B	1·11	1·50	97·16	
E	31	D. 4	0·07	2·25	97·70	
	17	C. 1-6	0·61	2·50	96·70	
F				10·00*		
				20·00*		
	3	"VII"	0·18	48·60	51·00	
				80·00*	20·00	

* Stated by Faraday to have been made but so far no trace has been discovered.

The specimens under Hadfield Research, Numbers 14 and 46, represent the two Faraday steels from which the author produced the miniature knives described in this book.

The specimen under Hadfield Research Number 15, represents the razor produced by the author and made from the Faraday steel.

of the steels containing 10, 20, and 80 per cent. Pt., which are mentioned in the Stodart-Faraday papers of 1820 and 1822, as these have not been found.

As regards the eight specimens in division "A" of Table XVI. it will be seen that with one exception, No. 61/E. 3-2, the percentages of carbon and platinum obtained can be regarded as wonderfully regular, that is specially in view of the simple melting apparatus employed by Faraday.

The next two divisions, "B" and "C," represented platinum from 0·90 to 1·20 per cent.; division "D," 1·34 to 1·50 per cent.; division "E" 2·25 to 2·50 per cent. The author found no less

Table XVII

Number of the Various Tests carried out on the 79 specimens of Faraday's "Steel and Alloys"

	On Faraday's specimens.	Additional on other steels for comparison.	Total.
Chemical analyses	434	Nil	434
Micrographic Examination (including 30 photomicrographs)	46	Nil	46
Specific gravity	21	Nil	21
Hardness tests (30 or so other tests were made, not recorded in the paper)	92	Nil	92
Tensile	4	2	6
Specific magnetism	22	Nil	22
Electrical resistance	3	2	5
Dilatometer (Chevenard)	4	2	6
Heating and Cooling Curves	3	2	5
Corrosion Tests	5	2	7
	634	10	644

than 48·60 per cent. platinum in specimen No. 3/"VII." (division "F"), and the carbon in this is specially low, only 0·18 per cent.

The addition of rhodium to the amount of 1·20 per cent. in Specimen No. 9/B.6 has raised the tenacity slightly, but there is a more than commensurate falling off in the ductility. At the same time, the yield point is quite definitely lowered from 29 to 22·5 tons per square inch as compared with unalloyed carbon steel. Rhodium, therefore, in its effect on the tensile properties appears, unlike platinum, to have a detrimental effect. Although the blemish referred to on the test-piece from No. 22/C.2-2 (2·18 per cent. Ni, 0·75 per cent. Au) was likely to interfere with a true dis-

play of the properties of this material, the test was carried out. Fracture, however, occurred at the defect with an elongation of only 2·5 per cent. after a load of 54·5 tons per square inch had been reached. Clear indication of the yield point was obtained at 40 tons, showing considerable increase as compared with the 28·5 tons shown by the corresponding carbon steel 1584C/2. From the ball hardness of 300 a true tenacity of about 65 tons per square inch can be deduced, as compared with 51 tons for the carbon steel. While therefore the full effects of the nickel and gold additions upon the tensile properties are not determined, it is clear that in the yield point and tenacity there is a marked increase.

In all, the number of tests, chemical, physical and mechanical, applied to these Faraday specimens is 634, or, if a further ten made on other steels for purposes of comparison are included, a grand total of 644. The number of tests of the separate kinds is summarised in Table XVII.

Preparation of Knives and Razor from Faraday's Steel

As a fitting addition to the examination of these specimens of Faraday's "Steel and Alloys," produced more than a century ago, and having in mind the direction taken by his efforts, it was felt that some attempt should be made, if possible, to prepare from selected pieces actual articles of cutlery, including razors. With the assistance of the famous Sheffield firm of cutlers, Messrs. Joseph Rodgers & Sons, Ltd., including their representative, Mr. R. T. Hartley, to whom best thanks are offered for the great amount of care and attention he and his firm have devoted to the experiments, the author has been enabled to prepare a razor and twenty miniature knives. These articles of cutlery were produced in the following manner :

Miniature Knives.—As mentioned in the section on forging, from the Faraday specimen No. 14/C.1-3, containing 0·94 per cent. carbon and 0·74 per cent. platinum, flat section strips, 0·027 inches × 0·20 inch, were forged by the author, and these strips formed the material for making the blades of the miniature knives. The selection of the steel used was determined by the fact that it contained platinum, and that its various properties had been rather fully examined. Its microstructure is shown in photomicrographs Nos. PM.13, representing the steel as forged by Faraday, and PM.25, after it had been forged by the author. The Chevenard dilatometer diagram appears in Fig. 3, and the ordinary heating and cooling curve in Fig. 5.

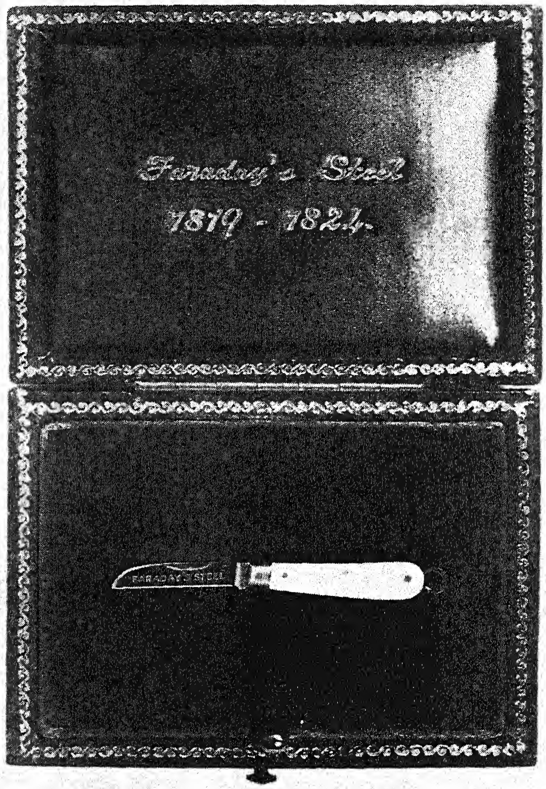
The hardening qualities of the steel were tested on a small portion of the trimmings from the edge of the strip, by heating to

750° for two minutes and quenching in water. Confirming the expectations derived from the dilatometric examination, the steel was fully hardened, having a Brinell hardness of 710, thus indicating no essentially apparent difference in the behaviour of this platinum steel as compared with carbon steel of similar carbon content. No change was therefore found necessary as compared with normal practice in the preparation of the knife blades.

While owing to the limited quantity of steel available these knives, one of which is shown in Plate XLVIII., are only miniatures, their construction and method of manufacture are in every way similar to those used for a Sheffield pocket knife of normal size, and with the same skilled workmanship which has been continued from the time of Chaucer, when the famous poet in his *Canterbury Tales* related of one of his characters that " A Shefeld thwytel bare he in his hose." It will be seen that the finished knives represent steel which has been forged three times, first by Faraday, then by the author, and finally by Messrs. Joseph Rodgers & Sons. Although actually the quantity of steel used in making these twenty knives was only 23 grams, or less than 1 ounce, the blades are hardened and tempered, and within the limitations of their size are quite capable of giving a good account of themselves. The Brinell hardness determined on one of the finished blades shows a figure of 600 near the cutting edge and 520 near the back of the blade.

Razor.—The selection of a specimen from which to prepare a razor was specially limited, but No. 15/C.1-4 showed the most promise of giving a successful result. Besides containing 0·69 per cent. of platinum, its carbon content of 0·94 per cent. might be expected to give it full hardening properties. Its composition, in fact, was closely similar to that of Specimen 14/C.1-3, selected for making the knives. This Specimen 15/C.1-4 also seemed fairly free from seams, and with successful behaviour in forging its weight was just sufficient to produce the necessary amount of material for a blank suitable for a razor of usable size.

The preparation of the V-section bar necessary as the first stage has been described in the section on forging. Although great care was taken, the bar obtained was rather less in weight than was hoped for, and contained some imperfections which could not be avoided. For a full-size razor some 65 grams were required, the piece obtained weighing 55 grams. Messrs. Rodgers & Sons, however, successfully overcame this difficulty, and were able to prepare from this bar the razor shown at E in Plate LIII., which, although not of full size, is nearly so. By careful management it was arranged so that the defects in the bars were kept clear from the blade portion and appear, although not very prominently,

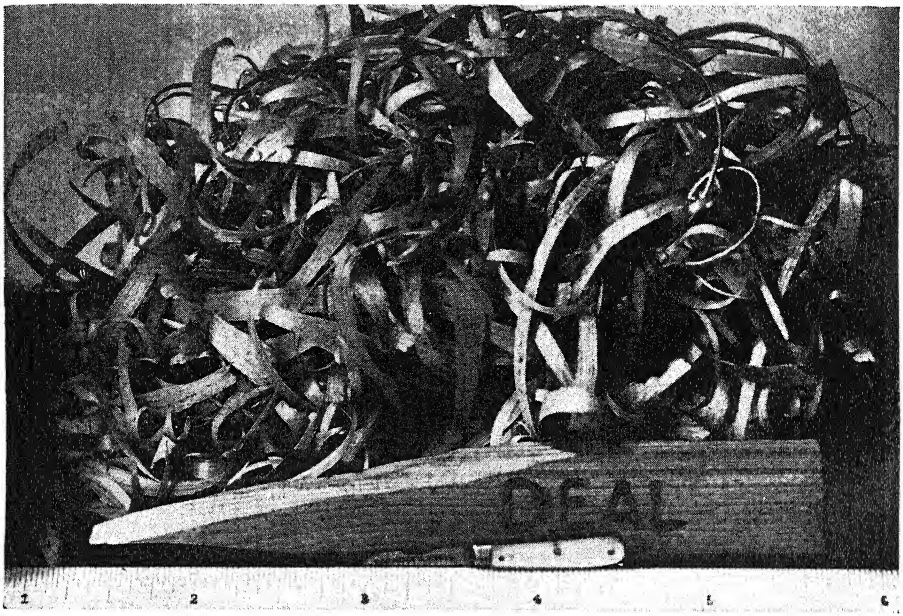


Full Size.

MINIATURE KNIFE PREPARED FROM FARADAY'S STEEL MADE 1819–1824.

The blade weighs one-hundredth of an ounce and the complete knife one-twentieth of an ounce.

[*To face p.* 212.



SHAVINGS CUT BY THE MINIATURE KNIFE ILLUSTRATED, MADE OF FARADAY'S STEEL.

The blade of this knife weighs only one-hundredth of an ounce, the complete knife weighing one-twentieth of an ounce. The shavings, cut from a block of deal, weigh about eighty times as much as the blade itself. After producing these shavings the blade was still in excellent condition.

To face p. 213.]

in the tang. In forging, the steel proved rather softer than the usual type used for razors. This razor has since proved its merits in actual use, as will be found described in a later section.

The Hadfield Research on the Ten Later Specimens of Faraday's "Steel and Alloys"

The specimens forming the subject of this research had been deposited with the Science Museum, South Kensington, and by the kindness of their owner, Mr. A. Evelyn Barnard, and of Colonel Sir Henry Lyons, F.R.S., the Director of the Science Museum, they were placed at the author's disposal for full examination. For purposes of distinction, they were numbered by the author from 1 to 10, No. 1 being the "Faraday-Stodart-Barnard-Indian Wootz" razor, while Nos. 2 to 10 proved to be some of the exceptionally interesting specimens mentioned by Faraday in his diary notes of November 3rd, 1823, referred to on p. 125 of this book. These nine specimens, particulars of which are given in Table XVIII., and which are illustrated in Plate L., weighed only 162·28 grams, or about 5¾ oz., and, although the number and nature of the tests possible with such small amounts of material were limited, useful information has undoubtedly been obtained. After the various examinations and tests had been made the remaining weight was 143·36 grams (5 oz.), only 18·92 grams (¾ oz.) having been used up in the research.

It is specially gratifying that these specimens include some of the high percentage alloys formerly believed to be missing, and as regards the low percentage of carbon in four of the specimens, viz., 0·07, 0·10, 0·12 and 0·18 per cent., this affords further definite proof of Faraday's wonderful operative skill with his "Blast Furnace."

Description of Specimens.—No. 1 in this set of specimens is the razor illustrated in Plate LIII. As explained on p. 239, it was made by Stodart from an alloy prepared by Faraday, either at the Royal Institution or in the large-scale experiments at Sheffield, and evidently consisting of a base of Indian wootz steel alloyed with 1·10 per cent. of platinum. The razor bears Stodart's name, also the wootz sign, and, as shown by its inscription, it was subsequently presented by Faraday to his nephew James Faraday Barnard.

The five specimens Nos. 2 to 6 inclusive are each in the form of unusually small "ingots," weighing only from 6·27 to 25·22 grams, all in the cast condition, that is, just as cooled down in the crucible, the hemispherical form which they have taken on their underside showing this to be the case, that is, they have not been subsequently

TABLE XVIII—*General Particulars of the Ten Later Specimens of Faraday's and Hardness.—*

Specimens Nos. 2, 3, 4, 5, 6 and 7 are in the cast

HADFIELD NO.	FARADAY'S MARK.	DESCRIPTION IN FARADAY'S DIARY AND PAPERS: The words in inverted commas appear in Faraday's own handwriting in his Diary, November 3rd, 1823.		WEIGHT: Grams.	CHEMI		
					C.	Si.	P.
1	 STOD ART This represents the Indian characters for Wootz steel.		Razor containing Platinum and having Wootz steel as its base.		0·84		
2	IX	"Steel 50, Rhodium 50."	Small ingot 0·55″ dia. × 0·28″ in depth.	6·28	·12		
3	VII	"Steel 50, Platinum 50."	Small ingot 0·65″ dia. × 0·41″ in depth.	12·55	·18		
4	No mark		Small ingot, oval, 0·93″ × 0·73″ × 0·25″ in depth.	10·11	·28		
5	V	"Iron with 3% Rhodium."	Small ingot 0·82″ dia. × 0·68″ in depth.	25·22	·11	·02	·106
6	IVI	"Pure iron fused."	Small ingot 0·85″ dia. × 0·54″ in depth.	23·24	·07		·053
7	No mark	"Crystalline carburet of iron."	Small ingot 1·38″ × 1·13 × 0·59″ in depth.	37·74	3·46		
8	II	"Platinum and steel welded."	Small bar 0·20″ × 0·18″ × 1·65″, consisting of steel and platinum united by welding transversely.	10·77			
9	I	"Platinum and steel welded."	Small bar 0·28″ × 0·16″ × 1·75″, consisting of steel and platinum united by welding longitudinally.	23·23			
10	III	"Twisted and forged steel to imitate Damascus."	Small flat plate 0·45″ × 0·18″ × 1·70″ with etched surface showing a damascene pattern.	13·14	0·33	0·22	0·10

Total = 162·28 ozs.

* After heating to 750°C. for 15 minutes and cooling in air.

"*Steel and Alloys,*" *including one Razor, with their Analysis, Specific Gravity*
Period 1823.
condition ; Nos. 8, 9 and 10 represent forged material.

CAL ANALYSIS.							SPECIFIC GRAVITY.	BRINELL HARDNESS.	DESCRIPTION ON WRAPPER. The words in inverted commas appear in Faraday's own handwriting.†
Mn.	Cu.	Pt.	Pd.	Rh.	Fe.	Total.			
·05		1·10			97·80			TANG. End. 310 / 320; Near 600 / 650 BLADE. Back 530; Edge. 520 / 575	"Faraday-Stodart-Barnard-Indian Wootz Steel." No wrapper but the razor is marked STOD ART
				48·8	50·60	99·520	9·22	350	"Iron with 3 Rhodium."
		48·60			51·00	99·780	9·83	305/340	"Steel with Rhodium equal parts."
	·80		22·70		75·50	99·280	8·22	386/392 *	"Iron with 3 Nickel" (but proved to be Palladium).
Nil		Trace	1·25		98·20	99·686	7·88	170/185	(Proved to be 1·25% Rhodium.)
"		Precious metals absent.			99·70	99·823	7·81	100/140	"Pure iron fused."
							7·00	137/143	No wrapper.
							12·91	216/286 steel portions 74/92 platinum.	"Steel and Platina united by welding."
							12·70	228/265 steel portions 77/83 platinum.	
					99·10	99·75	7·75	232/365 light coloured area. 270 darker bands.	"Steel Damas" (outside). "Attempt to imitate Damask steel" (inside).

† The information presented in the last column is included for purposes of record, but as explained in the text, the wrappings of several of these specimens have evidently been interchanged at some period during the last century.

forged. It will be remembered that, as shown in the author's previous research, this is in accordance with Faraday's regular procedure, some amongst the seventy-nine specimens having been of this same form although larger in size.

TABLE XIX

FURTHER "STEEL AND ALLOYS" MADE BY FARADAY

Period 1823

BALANCE SHEET relating to the disposal of the 9 Faraday steel specimens, also showing the amount of steel used in carrying out the author's research.

(A) The total of the weight of the specimens before the research was . . . . . 162·28 gm. (5¾ oz.)

(B) The total of the weight of the specimens remaining after the research was . . 143·36 gm. (5 oz.)

(1) The following material is still available :

	Grams.	Per cent.	Grams.	Per cent.
(A) Untouched portions of the original specimens still remaining . . .	141·48	87·18	143·36	88·34
(B) Micro section cut off Specimen No. 7 . . .	1·88	1·16		

(2) The following sections (C) and (D) represent material which has been used up and is non-recoverable :

	Grams.	Per cent.	Grams.	Per cent.
(C) Drillings (portions of which are still available) from which 36 analyses were made	11·27	6·95	18·92	11·66
(D) Waste represented by heat scaling also loss due to corrosion and in polishing	7·65	4·71		
TOTAL, representing the original weight of the 9 specimens			162·28	100·00

Marking.—Four of these five specimens are marked by Roman numerals, cut into the edge apparently with a file. Individually the visual character of these small "ingots" is as follows :—

Specimen No. 2 (48·80 *per cent. Rhodium*).—This specimen has most of its upper surface mirror polished with no sign of rust, and is marked IX. The writing on the paper wrapper, which analysis subsequently shows clearly has been interchanged and probably belongs to Specimen No. 5, says: "Iron with 3 rhodium." The

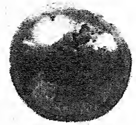
FURTHER NINE SPECIMENS OF "STEEL AND ALLOYS" PREPARED BY FARADAY 1819–1824.

Total weight of specimens 162·28 grams.

The descriptions of the specimens as shown by the sentences in inverted commas, that is, excepting those for Nos. 4 and 7, are from Faraday's diary and in his own handwriting under date November 3rd, 1823 ($5\frac{3}{4}$ ozs.).

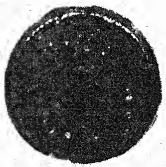
Full analyses of these specimens are presented in Table XVIII

No. 2
"Steel 50 Rhodium 50"

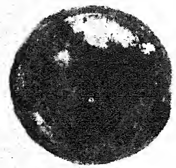


No. 3
"Steel 50 Platinum 50"

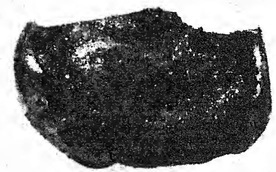
No. 4
Iron with 22.70% Palladium



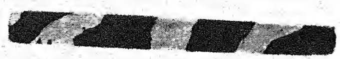
No. 5
"Iron with 3 per cent Rhodium"



No. 6
"Pure Iron Fused"



No. 7
Cast Iron.



No. 8

No. 9

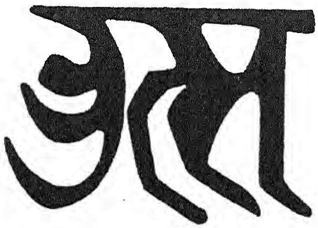
Platinum & Steel Welded"

No. 10
"Twisted and Forged Steel to imitate Damascus"

The first group of seventy-nine specimens is shown in Plates XXIX. and XXX. Specimen No. 7 is Faraday's famous "Carburet of Iron."

Platinum Steel.

Rhodium Steel.



Wootz.

FIG. 12.—SPECIAL MARKINGS ON FARADAY SPECIMENS.

To face p. 217.]

specimen actually contains 0·012 per cent. carbon, 48·80 per cent. rhodium.

Specimen No. 3 (48·60 *per cent. Platinum*).—This also has part of its upper surface mirror polished with one small patch of dark brown rust. The remainder is rough and unpolished, but bright, and showing in parts a dendritic structure. The under surface is rough and pitted. The mark in this case is VII., and the wrapper, apparently belonging actually to No. 2, bears the description "Steel with rhodium equal parts." The actual composition is 0·18 per cent. carbon, 48·60 per cent. platinum.

Specimen No. 4 (22·70 *per cent. Palladium*).—This specimen is flatter in form than the others, and the lower portion has evidently been broken away. The upper surface is mirror polished but badly tarnished, specially round the edges and in spots in the centre portion. The sides have also been polished to a less degree, and are badly tarnished. This specimen bears no mark, but the writing on the wrapper, which again evidently does not belong to this specimen, says "Iron with 3 Nickel." The actual composition is 0·28 per cent. carbon, 22·70 per cent. palladium.

Specimen No. 5 (1·25 *per cent. Rhodium*).—The appearance of No. 5 is very noticeably different from that of the preceding ones. Its surface is entirely "black," except a small portion of the under surface, which is bright. The upper surface bears a pattern which may be due to a peculiar formation resulting from the shrinkage of the metal in cooling. It seems more probable, however, that an attempt has been made by means of a die to impress some form of design on the surface. The serrations round the edge appear almost too regular in form and spacing to have been produced merely in cooling.

The bottom surface of the specimen is rather irregular in shape, that is, not so well conforming to the shape of the inside of an ordinary crucible. Possibly in this case the crucible had deformed owing to a rather high melting temperature, as appeared to be the case with Specimens Nos. 2/A.2 and 10/B.7 of the earlier research. This Specimen No. 5 is marked V., there is, however, no writing on the wrapper.

Specimen No. 6 (*Pure Iron Fused*).—The underside of Specimen No. 6 is black, with a number of excrescences and red-rust patches. The upper surface has evidently been polished, but is now considerably rusted. The mark in this case is VI. There is no writing on the wrapper.

Specimen No. 7 (*Crystalline Carburet of Iron*).—This is also a cast specimen, rather larger than the foregoing, but its appearance

suggests that the metal was in this case poured out into a crucible and solidified before it could completely take the form of the latter. A portion of the specimen has been broken off, the fracture having the appearance of cast iron, with patches of rust. Otherwise the surface is entirely black, the upper surface and hollows being almost entirely rusted over, and the under surface rusted in specks. There were no marks on the specimen, and no writing on the wrapper. This specimen represented Faraday's famous "Crystalline carburet of iron" referred to more fully on pp. 235 and 249.

Specimens Nos. 8 *and* 9 (*Platinum and Steel Welded*).—The wrapper containing two of the remaining specimens, Nos. 8 and 9, bore the words "Steel and Platina united by welding," and the specimens themselves are similar to those referred to in some detail in the paper by Stodart and Faraday on "Experiments on the Alloys of Steel, made with a View to its Improvement," published in 1820 in the *Quarterly Journal of Science*, where it is stated that wires of platinum and steel, of about equal diameter, were packed together and, by an expert workman, were perfectly united by welding. This was effected with the same facility as could have been done with steel and iron. On being forged, the surface polished, and the steel slightly acted on by an acid, a very novel and beautiful surface appeared, the steel and platinum forming dark and white clouds: they further state that some of the largest of the steel clouds had much the appearance of being alloyed with a portion of the platinum, and that a more correct survey of the surface, by a high magnifying power, went far to confirm this curious fact.

In Specimens Nos. 8 and 9 the platinum shows up bright in contrast with the darker steel. While generally the lines of demarcation between the two metals indicate good welding, at several places the junction is somewhat imperfect. Specimen No. 8 is distinguished from No. 9 by the junctions being more or less transverse to the length, those in No. 9 being longitudinal. The cloudy appearance referred to by Faraday is more pronounced in No. 9 than in No. 8. They are also marked individually II. (No. 8), and I. (No. 9).

Specimen No. 10 (*Steel to Imitate Damascus*).—The wrapper on the last specimen, No. 10, bears two written inscriptions. One on the outside "Steel Damas," and the other inside, "Attempt to Imitate Damask Steel."

Faraday, in the paper referred to, describes two separate methods by which he was able to produce specimens, each having on etching with dilute sulphuric acid a beautiful damask.

One of these methods consisted in fusing "good steel" with

a small proportion of "alumine alloy," and forging the button obtained. The alumine alloy had previously been produced by heating together iron carburet and pure alumina.

In the other case a similar procedure was adopted, but in the place of the alumine alloy, part of a button of menachanite was fused with the steel. This button was the result of heating menachanite with charcoal in an attempt to reduce the titanium. In neither of these accounts is there, however, any reference to twisting of the material such as appears in the description of the specimen in Faraday's Diary. The actual method of its production is therefore in some doubt.

This specimen, as Plate L. shows, has one flat surface, polished and etched, displaying a distinct damask pattern. One edge, which is not seen in the photograph, is also prepared in the same way, but the pattern in that appears less distinct. The remainder of the surface is rough and with rust patches, which also appear on the edges of the damask portion. The mark on this specimen is III.

Chemical Analyses and Physical Tests

Difficulties Encountered.—Such small specimens offered even more difficulty in conducting analyses and tests upon them than the collection of seventy-nine specimens—all of which, with the exception of specimens Nos. 1/A.1, 2/A.2 and 3/A.3, were in the forged condition—examined in the previous part of the author's research. Nevertheless, quite a useful amount of information has been obtained, thirty-six separate analyses being carried out, as shown in Table XX.

Besides chemical analyses on Specimens Nos. 2 to 7, also No. 10, micro examination and tests for specific gravity and hardness were made upon all the specimens, Nos. 2 to 7 being in the cast condition. Indications as regards resistance to corrosion and to heat scaling have also been obtained in the case of Specimens 2, 3 and 4. Naturally, Specimens 8, 9 and 10, representing attempts to weld platinum to steel, also to imitate damascene steel, did not call for quite the same methods of examination as the rest, and no chemical analysis has for the present been made of Nos. 8 and 9.

Methods Adopted.—In the chemical analysis, the experience gained in the larger research was of considerable value, but the analysis of the alloys with high percentages of rhodium, platinum and palladium called for some modification of the methods previously used, due in the first place to the insolubility of these alloys in dilute sulphuric acid. It may be of interest, therefore, to describe briefly the procedure actually adopted for these richer alloys.

Owing to the very limited amount of material available, the whole of the nine specimens only weighing 162·28 grams ($5\frac{3}{4}$ oz.), the determinations of iron and of the precious metals were carried out on the same accurately weighed portion of sample, obtained in the form of drillings. About 0·3 gram of sample was dissolved in aqua regia, 7 c.c. of concentrated sulphuric acid added, and the

TABLE XX

NUMBER OF ANALYSES MADE ON THE NINE FURTHER "STEEL AND ALLOYS" SPECIMENS MADE BY FARADAY

Period 1823

Details of the number of different determinations making up the total of 36 analyses carried out.

		Check Analyses.	Total.
Carbon	7	3	10
Silicon	3	–	3
Phosphorus	3	1	4
Manganese	2	–	2
Copper	1	–	1
Aluminium	1	–	1
Titanium	1	–	1
Platinum	2	–	2
Palladium	1	–	1
Rhodium	2	1	3
Scoria	1	–	1
Iron	6	1	7
	30	6	36

solution evaporated to fumes. The bulk was then brought to 100 c.c. with water, and 20 c.c. of 5 per cent. sulphurous acid solution added. The liquid, in each case, remained clear on boiling, proving the absence of gold.

To avoid a bulky precipitate with hydrogen sulphide, 2 grams of metallic zinc were now added to precipitate most of the metals of that group, and 3 c.c. of concentrated sulphuric acid added to compensate for the acid neutralised by the zinc. The bulk was adjusted to 350 c.c. with distilled water, hydrogen sulphide passed to complete the precipitation, the liquid brought to simmering, then cooled, filtered, and washed with 2 per cent. sulphuric acid

containing H_2S. The filtrate was again saturated with H_2S and the solution boiled free from the gas, cooled and titrated with N/20 potassium permanganate. The weight of iron thus accounted for was corrected for the traces of iron contained in the zinc and retained by the H_2S precipitate.

To make sure that all precious metal had been removed by the H_2S, the solutions after titration were rendered alkaline with sodium hydroxide, again gassed with H_2S, and afterwards rendered acid with sulphuric acid. In No. 2, a further quantity was obtained, but not in No. 3 or No. 4. The hydrogen sulphide precipitates, including the further precipitate in the case of No. 2, were gently ignited. The residues were boiled with a little hydrochloric acid. No. 2 and No. 3 were scarcely attacked, only traces of iron being extracted by this treatment. The amounts were determined and added to the iron figures. The metallic residues from No. 2 and No. 3 were then gently ignited in air, reduced in hydrogen, and weighed.

The residue from No. 2 proved to be unattacked by dilute aqua regia, but an appreciable amount was dissolved by strong aqua regia, giving a pink solution, indicating rhodium. This solution was tested in portions for platinum and for palladium and silver by the ammonium chloride and potassium iodide tests respectively. Platinum, palladium and silver were proved absent. A portion of the main precipitate was fused with potassium hydrogen sulphate. The metal was completely attacked, and the dissolved sulphate gave the characteristic pink colour with hydrochloric acid, confirming rhodium.

The metallic residue from No. 3 was certainly attacked by dilute aqua regia, but as the action was slow, the concentration of the aqua regia was increased. Complete solution was obtained. A portion of the solution was tested with the potassium iodide test, proving the absence of silver and palladium. Another portion was tested with ammonium chloride, the pure yellow colour of the precipitate obtained indicating platinum and the absence of rhodium and iridium.

The residue from No. 4 proved to be partly soluble in hydrochloric acid, and after addition of dilute aqua regia was readily dissolved, giving a reddish-brown solution, suggesting the presence of palladium. The solution was evaporated to a syrup and diluted. Silver was proved to be absent. The acidity was adjusted to 20 per cent. concentrated hydrochloric acid by volume, and 10 per cent. solution of potassium iodide added until no further precipitate was produced. The solution was boiled, cooled, and filtered. The black

precipitate of palladous iodide was washed with 5 per cent. hydrochloric acid, dried, ignited in air, and coal gas passed into the crucible while hot. After cooling, the metallic residue was weighed as palladium.

The filtrate from the palladium iodide was examined and a further 0·0014 gram of precious metal recovered—equal to 0·50 per cent. on 0·280 gram. In addition, a small percentage of copper, which amounted to 0·80 per cent., was separated.

The method for the determination of alumina and slag, or "Scoria," in specimen No. 10 representing an attempt by Faraday to imitate damask, with also the procedure for the determination of aluminium or titanium was as follows :—

One gram of drillings was dissolved in dilute nitric acid, sp. gr. 1·16, at about 90° C., diluted with water, and filtered. The residue was washed free from iron with 5 per cent. nitric acid and water, ignited and weighed. The amount obtained was so small that the separation of alumina from it was not proceeded with.

To the filtrate from the "scoria" obtained as above, 10 c.c. of hydrochloric acid were added and the solution evaporated to dryness, the residue baked, cooled and redissolved in hydrochloric acid, and the silica removed by filtration. The filtrate from the silica was neutralised with ammonia, and 30 c.c. of a saturated solution of sulphurous acid in water were added. The excess SO_2 was boiled off, then 2 c.c. of 10 per cent. ammonium phosphate along with 10 grams of sodium thiosulphate added, and boiled for three minutes. Five c.c. of acetic acid were then added, and the boiling continued for a further twenty minutes. The solution was filtered and washed, ignited and weighed. The weight obtained was only 1 mg., so the determination was not further proceeded with.

The samples for chemical analysis were all obtained by drilling.

Results of Analyses.—The results of these analyses are given in Table XVIII. Specimens Nos. 2, 3 and 4 proved to be particularly interesting, as being representative of the high percentage alloys of iron with the precious metals rhodium, platinum and palladium, referred to by Faraday as having been made by him, although not found among the specimens which had been preserved in the wooden box at the Royal Institution.

Specimen No. 5 is also alloyed with rhodium, but only in the comparatively small amount of 1·25 per cent., while No. 6 is quite unalloyed. Nevertheless, as shown later, this is most interesting, representing, as it does, "pure iron" (the term adopted by

Faraday), which he had melted, a remarkable feat for him to accomplish with his little "blast furnace," calling, as it did, for an extremely high temperature.

All these "ingots" are well melted and are remarkably low in their carbon content, which adds still further to our admiration for Faraday's skill in this direction, of which there were indications in the previous research, notably in the case of Specimen 31/D.4, containing 2·25 per cent. platinum and only 0·07 per cent. carbon. These steel alloys low in carbon would require much higher melting temperature and much skill would be needed to avoid the absorption of carbon and to produce sound material. It must be remembered Faraday had no help to effect soundness such as the use of silicon, aluminium or manganese in the form of ferro alloys.

After a very full and careful examination of Specimen No. 10 by the method just described, no aluminium or titanium were found to be present, and only about 0·20 per cent. of scoria. The actual analysis gives the following results :—

C.	Si.	P. (approx.)	Scoria.	Al.	Ti.	Fe.	Total.
0·33	0·22	0·10	0·20	Nil.	Nil.	99·1	99·75 %

Five holes were drilled in the specimen, and in drilling the middle one it was noticed that the metal was distinctly harder than in the case of the other portions.

Specimens Agree with Descriptions in Faraday's Diary.—It became clear from the analyses that, in view of Faraday's marking in Roman numerals, and the description on some of the wrappers, there must be a definite connection between the specimens and those catalogued also under Roman numerals in Faraday's diary under the date November 3rd, 1823.

In Table XVIII. the descriptions in the diary have been associated with the seven specimens bearing the corresponding marks. While the agreement is not perfect it is sufficiently so to leave no doubt that these specimens are the actual ones referred to in the diary. This enables the author to add that in regard to the various elements which Faraday stated he had used in making these alloys, these results, with but two exceptions, complete the records given by Faraday in his papers, a really remarkable result in view of the long interval of time—over a century—since the steel specimens were made and the many dangers and risks they must have run of becoming lost. The differences are that Specimens VII. and IX. are indicated as alloys of steel though

their low carbon clearly shows an iron base to have been used. The actual percentages of platinum and rhodium respectively, however, agree closely with the description. No. V. also shows only 1·25 per cent. of rhodium in place of the 3 per cent. in the description, the latter naturally having reference to the amount added. This may possibly be explained by an excessive loss of rhodium in melting.

Specimens VIII. (steel 20, platinum 80), and VI. (iron with 3 nickel), however, are not found among the present collection, their place having been taken by an alloy of iron with 22·70 per cent. of palladium (author's Specimen No. 4) and a fragment of cast iron (author's Specimen No. 7). The absence of the 80 per cent. platinum alloy is also to be regretted, but as a substitute the palladium alloy is specially welcome, since it increases to eight the number of special metallic elements alloyed with iron found among the alloys now remaining which have been made by Faraday. None of the previous specimens examined by the author has been found to contain palladium.

Table XVIII. further shows the fact previously mentioned, that some of the wrappers as handed to the author have at some time been interchanged, a fact which is perhaps not surprising in view of the similarity in form of several of the specimens.

Although the specimens were small they afforded a means of obtaining some idea of quite a number of physical characteristics of such alloys in a more definite way than was possible with the limited facilities available when Faraday was carrying out his researches.

Specific Gravity.—The determination of specific gravity, which was made on all the specimens, actually preceded the chemical analysis, and was carried out upon each of the specimens as a whole. In the case of Nos. 8 and 9, the figures obtained are of course more properly described as their average densities. These results are presented in Table XVIII. As a matter of interest they may be compared with Faraday's data in Table I. on p. 121.

Hardness.—Hardness tests were made on all the specimens by the Diamond Pyramid method, using a load of 10 kilos. The figures obtained have been converted into the Brinell scale by means of a calibration of the apparatus made for that purpose, as in the case of the tests on the 79 specimens, p. 175.

Additional hardness figures were obtained on Specimens Nos. 2, 3 and 4 after they had been heated to 750° C. for the purpose of

ascertaining their degree of resistance to heat scaling, and the figures will be found recorded in Table XVIII.

Magnetic Quality.—All the specimens are magnetic, this being understood, of course, as regards the welded specimens to apply only to the steel portions.

The form and size of these specimens, and their variation from one to another, made a precise comparison of their magnetic properties rather difficult, and still more so any attempt to obtain accurately their specific magnetism.

This difficulty was met as far as possible, and figures obtained in the following way: The specimens of real interest were the alloys Nos. 2, 3, 4 and 5. A specimen of Swedish Charcoal Iron (S.C.I.), 99·85 per cent. Fe, was prepared as nearly similar in form and size as possible to each of these specimens. Each specimen was hung on a spring balance in a position on the axis of, and just outside a vertical cylindrical solenoid, and the magnetic pull on the specimens compared with that of the corresponding specimen of S.C.I.

The solenoid was of 1 inch internal diameter and 18 inches in length, and with the current used gave a magnetic field at its centre of 1,700 CGS units. Both the position of the specimen on the axis and its orientation were chosen so as to give the maximum pull. The slight difference in volume between the actual specimen and its corresponding piece in S.C.I. was corrected for by applying the theoretical law that the pull varies as the 3/2 power of the volume. Preliminary experiments had shown this law to hold closely.

Corrected in this way the magnetic pull on the four specimens, Nos. 2, 3, 4 and 5, was 102, 48, 92 and 92 respectively, taking the pull on S.C.I. as 100. The respective specific magnetisms, taken as proportionate to the square root of the pulling force, are therefore as follows: No. 2, 101; No. 3, 69; No. 4, 96; No. 5, 96.

Thus it will be seen that rather surprisingly the 48·8 per cent. rhodium alloy No. 2, and the 22·70 per cent. palladium alloy No. 4, notwithstanding their high percentages of these alloying elements, have a specific magnetism approximating to that of pure iron. No. 3, with 48·60 per cent. platinum is, however, definitely less magnetic than iron, reaching only 69 per cent. No. 5, which contains only 1·25 per cent. rhodium, gives a figure which, as might be expected, is not far short of that of pure iron.

Exact accuracy is naturally not claimed for these figures, and the rather surprising results obtained need confirmation by accurately made tests with special and suitably prepared specimens. It may be

said, however, that a rough check made with a hand magnet by applying it to the specimens, and also to their counterparts in S.C.I. in a precisely similar manner, gave quite similar indications.

Resistance to Corrosion.—By reason of the small amount of material available, the tests for corrodibility had of necessity to be of a simple character. On the other hand, they were all particularly interesting, specially as it was thought these specimens might represent those alloys of which Faraday had spoken as possessing considerable resistance to corrosion effects. As regards one of them, No. 2, it will be seen from the results of the author's tests that this specially proved to be the case.

These corrosion experiments were confined to the highly alloyed Specimens Nos. 2 (Rh), 3 (Pt) and 4 (Pd). The intention was to ascertain whether any of them showed any outstanding properties in this direction, rather than to attempt to assess those properties accurately, bearing too in mind the small nature of the specimens.

Atmospheric Conditions.—The specimens, which were repolished, were placed with the polished surfaces uppermost on a rubber pad, and exposed over the week-end (forty-eight hours) to the industrial atmosphere of Attercliffe, Sheffield. The weather was showery, the rain being heavy at times. (August, 1931 !)

Observations were confined to a visual inspection of the surfaces after exposure, these being as follows :—

No. 2 (·12 per cent. C., 48·8 per cent. Rh) had a rust stain on the edge, about $\frac{3}{8}$ inch long by $\frac{1}{8}$ inch wide, but was otherwise unaffected. It is quite possible that there may have been some physical reason for the slight attack at one spot. No. 3 (·18 per cent. C., 48·60 per cent. Pt) had similar rust stains at several places. In striking contrast was No. 4 (·28 per cent. C., ·80 per cent. Cu, 22·70 per cent. Pd), which had rusted over completely and evenly.

For comparison it may be stated that under similar conditions of exposure a polished surface either of high chromium steel or of the most modern nickel-chromium type of corrosion-resisting steel remains unaffected.

Results Obtained.—It is interesting to compare the behaviour of the alloys in this test with their recorded conditions as received by the author. When this is done it will be seen that on the whole the indications are similar as regards Nos. 2 and 3, although very markedly different in the case of No. 4. No. 2 as received was quite free from rust spots, while No. 3 had only one small patch of dark-brown rust, comparing with the completely rusted condition of the melted iron specimen No. 6. No. 4, on the other hand, which has

rusted badly in the present test, while rusted in patches, was decidedly superior to No. 6 in its condition as received. It is not safe, of course, to assume that during the intervening period of years these specimens had received equality of treatment, and too much reliance must not therefore be placed on this comparison.

Faraday's own observation is that equal parts by weight of steel and rhodium gave an ingot, which, when polished, exhibited a surface of the most exquisite beauty: the colour of this specimen is the finest imaginable for a metallic mirror, nor does it tarnish by long exposure to the atmosphere. He also stated that the same proportion of steel and platinum gave a good ingot, but a surface highly crystalline which rendered it unfit for a mirror.

This seems to provide further evidence that the two specimens Nos. 2 and 3, notwithstanding their low carbon and their descriptions in the diary (under date November 3rd, 1823) as steel alloys, are the identical ones referred to under the numbers IX. and VII., which marks they bear. Reference to the descriptions of the specimens as received by the author shows that No. 2 (48·8 per cent. Rh) had a clear polished surface, while No. 3 (48·6 per cent. Pt) had a dendritic structure which may quite well be the highly crystalline surface referred to by Faraday.

Sea-water Tests.—The interesting results under atmospheric exposure encouraged the author to try the resistance of these three alloys against sea-water, usually a rather potent corrosive agent. After polishing, they were each immersed in separate beakers in 100 c.c. of a 3 per cent. solution of Tidman's Sea Salt and left for forty-eight hours at room temperature. No. 2 (48·8 per cent. Rh) again showed the best result, the liquid after the test having very little sediment, while except for a small yellow stain on the polished surface the specimen was free from rust.

No. 3 (48·6 per cent. Pt) was stained over about half its polished surface, the remaining half being quite bright. There was, however, considerable sediment, due mainly to corrosion of the under surface of the specimen. In this respect No. 2 had an advantage, since its under surface is smoother and therefore less liable to attack. On the whole, however, the rhodium alloy, as in the case of atmospheric corrosion, appears to offer more resistance to the attack of sea-water than the corresponding platinum alloy. Both, however, so far as this short period test can indicate, show a creditable behaviour in this rather searching medium.

The relative performance of the palladium alloy No. 4 (22·70 Pd) is in marked contrast with its behaviour under atmospheric exposure. After the sea-water test about three-quarters of its

upper polished surface was covered with red rust, which could be easily rinsed off. The remainder of the polished surface remained untarnished. The comparatively smooth under surface and edges were generally tarnished. The amount of sediment, although considerable, was actually less than for the platinum alloy, notwithstanding the greater surface exposed to attack in this case.

Resistance to Acids.—As regards resistance to acids, the indication was obtained during the procedure for chemical analysis, that alloys Nos. 2 and 3, containing 48 per cent. of Rh and Pt respectively, were not readily attacked by any single acid, and had therefore to be dissolved in aqua regia. The remaining analysed specimens, Nos. 4 to 7, did not present any difficulty. As regards platinum, this is specially interesting, in view of the behaviour in contrast with its low percentage alloys with iron and steel noted in the earlier research. These, it will be remembered, dissolved in warm dilute sulphuric acid in a remarkably rapid manner, a fact previously noted by Faraday. It should be noted, however, that the same remark does not apply to the rhodium steel.

To follow up the indications obtained in the procedure for analysis, the author, utilising such simple means as were possible, carried out some definite tests on a few drillings from Specimens 2, 3 and 4 in the more ordinary mineral acids as follows :—

A few fine drillings were weighed and immersed for one hour in 40 c.c. of each acid, (*a*) at room temperature, (*b*) boiling. The acid solutions were diluted and filtered ; the residues dried and weighed. The filtrates were evaporated to fumes with sulphuric acid, cooled, diluted, and tested for both iron and the precious metal concerned. The results are given in Table XXI.

Results Obtained.—It will be noticed that the rhodium steel alloy No. 2 shows no loss of weight in either sulphuric acid test, cold or boiling, or in the nitric acid test, cold. There is, however, a slight attack of the alloy in each case during the period of one hour's attack. Had this period been prolonged there would no doubt have been an appreciable loss of weight. It is therefore safe to say that not one of the alloys is absolutely proof against any of these acids and their resistance does not approach that of pure platinum ; even in aqua regia the latter dissolves more slowly.

Nevertheless, these results show the iron-rhodium alloy No. 2 to have acid-resisting properties of definite merit, particularly against sulphuric and nitric acids. As regards the former, that is, sulphuric acid, this chemical agent provides a severe test for even the most modern ferrous alloys. Such alloys are, however, obtain-

able with complete resistance to nitric acid in all concentrations and at all temperatures. With hydrochloric acid, another chemical agent which is specially active with ferrous alloys, there is appreciable attack on the rhodium alloy, specially in boiling solution. It is interesting to note that, although against atmospheric corrosion this rhodium alloy is somewhat inferior to modern high

TABLE XXI

Resistance to Mineral Acids

Specimen No.	At Room Temperature.	In Boiling Acid.
	SULPHURIC ACID, SP. GR. 1·20.	
2. (48·80% Rh)	Faint trace of iron in solution. No loss in weight of drillings.	Faint trace of iron in solution. No loss in weight.
3. (48·60% Pt)	Trace of iron in solution. No precious metal. Loss in weight, 8%.	Fair amount of iron in solution, but no precious metal. Loss in weight, 32%.
4. (22·70% Pd)	Some iron in solution, but no precious metal. Loss in weight, 28%.	Similar to No. 3. Loss in weight, 28%.
	HYDROCHLORIC ACID, SP. GR. 1·1.	
2. (48·80% Rh)	A little iron in solution and a trace of precious metal. Loss in weight, 4%.	Small amounts of iron and precious metal dissolved. Loss in weight, 20%.
3. (48·60% Pt)	Small amounts of iron and precious metal dissolved. Loss in weight, 24%.	Similar to No. 2. Loss in weight, 20%.
4. (22·70% Pd)	Small amount of iron and trace of precious metal dissolved. Loss in weight, 10%.	Small amount of iron and traces of precious metal dissolved. Loss in weight, 14%.
	NITRIC ACID, SP. GR. 1·2.	
2. (48·80% Rh)	Only faint trace of iron in solution. Loss in weight, nil.	Traces of iron only, in solution. Loss in weight, 4%.
3. (48·60% Pt)	Traces of iron only, in solution. Loss in weight, 10%.	Fair amount of iron and some precious metal in solution. Loss in weight, 40%.
4. (22·70% Pd)	Almost completely dissolved. Only traces of residue left.	Complete solution.

chromium-nickel alloys of iron containing 18 to 20 per cent. chromium and 8 to 10 per cent. of nickel, its resistance to nitric acid is not so good. On the other hand, in its resistance to hydrochloric and sulphuric acids it is definitely better. Further tests have confirmed these results.

The results for the platinum alloy No. 3 are also, in the light of the period at which it was made, undoubtedly good. It is, however, not up to the standard of the rhodium alloy. It is curious to note that in this case the results are about the same in each (hot) acid, although the sulphuric acid test was distinguished from the others

by the fact that none of the precious metal (platinum) was found in the solutions.

The palladium alloy No. 4 is, as already noticed in the procedure for chemical analysis, definitely inferior to the others in its resistance generally to these acids. Its best result is, curiously enough, with hydrochloric acid, against which it is, in fact, superior to the platinum alloy. It is, however, readily soluble in nitric acid.

These alloys were further tested in a number of fruit juices, namely, lemon, plum and tomato juices, with the result that

TABLE XXII

Resistance to Heat Scaling

Specimen No.	Loss in weight.		Brinell Hardness after Heating.
	% of original weight.	per 100 sq. cm. of surface exposed.	
2. (·12% C. 48·80% Rh) . .	0·19	0·26	392, 410
3. (·18% C. 48·60% Pt) . .	0·27	0·36	250, 250
4. (·28% C. ·80% Cu. 22·70% Pd)	0·92	0·93	392, 386
For comparison :—			
Mild steel	—	0·53	
Heat-resisting steel of modern type	—	<0·02	

neither the rhodium nor the platinum alloys Nos. 2 and 3 was stained. Each of these juices, as is well known, badly stains an ordinary carbon steel knife blade in a few moments. The iron-palladium alloy No. 4, however, was found to be stained slightly, but not nearly to the same degree as ordinary carbon steel.

Resistance to Heat Scaling.—A simple test for resistance to atmospheric oxidation at a red heat was also applied to the same alloys. The repolished specimens, after weighing, were placed in a silica tube, which was already heated to 750° C., and was open to the air at both ends. After the specimens had reached temperature, they were allowed to remain in the tube for fifteen minutes, then withdrawn and cooled in air.

Each of the alloys was covered with a dark grey scale, and it was evident therefore that none had special claims as a heat-resisting material.

The scale was easily removed with the aid of a hard soap and water, after which the specimens were dried and reweighed. The losses in weight, in terms both of the original weight and of the exposed surface, are shown in Table XXII.

Metallographic Examination.—In all cases except Specimen No. 7, it was found possible to make this examination by polishing and etching a portion of the surface without cutting a section specially for the purpose. The normal procedure as described in the main research served in all cases except for Specimens Nos. 2 and 3, the etching reagent being dilute nitric acid. These two specimens, however, required aqua regia.

In the case of Specimens Nos. 8 and 9, on etching only the steel was affected, the platinum portions being unattacked.

The examination was made in every case on the specimens as received by the author, without further heat treatment.

A description of the microstructure appears in Table XXIII, those of the alloys Nos. 2, 3, 4 and 10 being reproduced in Plates LI and LII.

Discussion of the Results.—In summing up the information obtained from this research, as shown in Tables XVIII, XXI, XXII and XXIII, the various specimens will be dealt with individually, as follows :—

No. 2 (0·12 *per cent. C.*, 48·80 *per cent. Rh*).—One noticeable feature of this specimen was its hardness. Although normally a steel of 350 Brinell hardness can be machined by modern tools without much trouble, it was only with the greatest difficulty that this alloy could be drilled. In this respect it has something of the character of manganese steel, the material glazing under the tool. Whether due to the same cause, that is, a special capacity for hardening under the effects of deformation, was not readily ascertainable with such limited material.

As regards specific gravity, it is interesting to note that Faraday makes special mention of the figure he obtained, namely, 9·176, for an alloy obtained by melting equal parts of steel and rhodium (see Table I, p. 121). The figure is thus not far different from that of the present alloy, namely, 9·22, although the low carbon shows this has obviously been prepared from an iron base.

Taking the specific gravity of iron and of rhodium as 7·82 and 12·50 respectively, the calculated specific gravity of this present alloy would be 10·08. Thus, a volume expansion of something like 9 per cent. must have occurred on alloying.

This alloy offers a remarkable resistance to attack by acids, in some respects better than the most modern ferrous acid resisting

Table XXIII

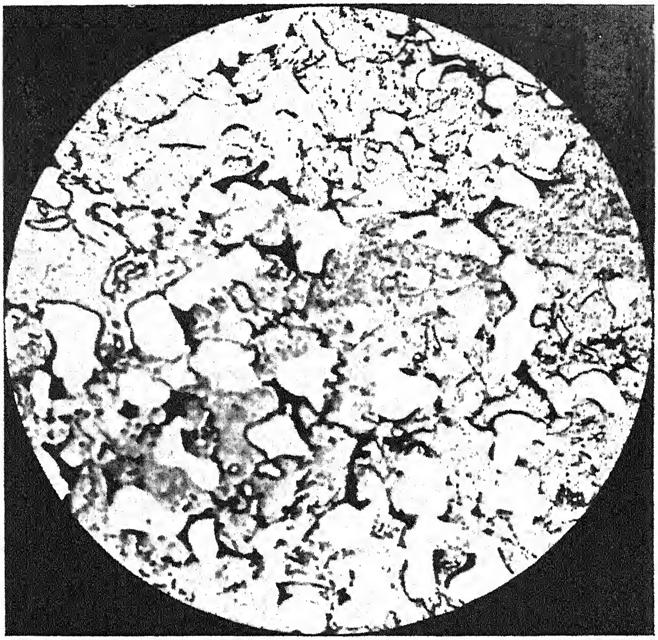
Metallographic Examination of the Nine further Specimens of Faraday's "Steel and Alloys."

The specimens were examined in the condition as received by the author.

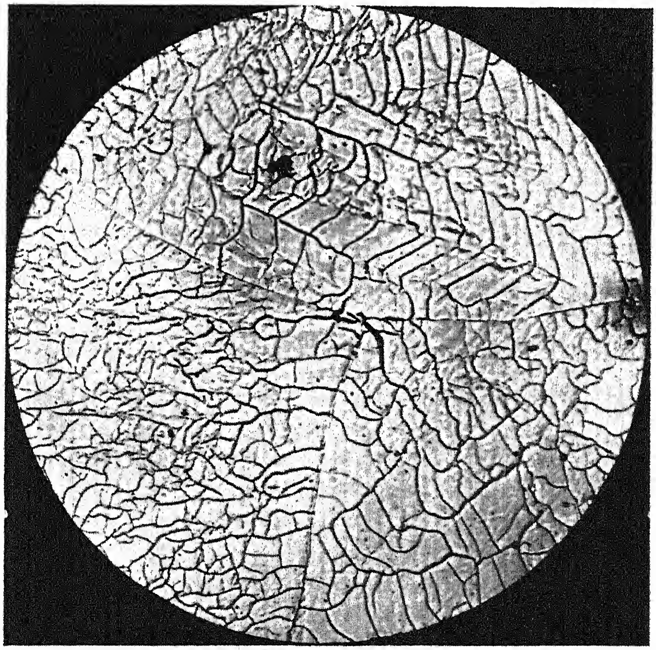
Specimens Nos. 2, 3, 4, 5, 6 and 7 are in the cast condition ; Nos. 8, 9 and 10 represent forged material.

Hadfield No.	Faraday's Mark	Chemical Analysis (per cent.) C	Cu	Pt	Rh	Pd	Fe	Photo-Micrograph No.	Description of Microstructure.
2	IX.	0·12			48·80		50·60	Fig. 2	The microstructure consists of a groundmass of sorbitic appearance, along with an almost equal proportion of white grains, which are not etched. In the grain junctions of the latter a small amount of carbide is segregated. The non-metallic inclusions are small, dark grey in colour, and very few in number.
3	VII.	0·18		48·60			51·00	Fig. 3	Two grain structures are present in this specimen ; a very coarse grain, within which are numerous smaller grains. No carbide appears to be present within the groundmass, what little there is being confined to the grain junctions. The non-metallic inclusions are small, fairly numerous, and dark grey in colour.
4	No mark	0·28	0·80			22·70	75·50	Fig. 4	The structure is most unusual in appearance. There is an indefinite grain structure in the groundmass on which are leaf-like shapes—sometimes tending to the form of a barb—composed of many lines of varied length. In their arrangement these leaf-like shapes produce, at low magnification, a structure somewhat dendritic in pattern. The non-metallic inclusions are similar to those in Nos. 3, 5 and 6.
5	V.	0·11			1·25		98·20		The structure consists of ferrite and pearlite grains. The ferrite grains are not equiaxed, but long and stringy in appearance, often interlocking. The pearlite grains are also long and narrow, following the outline of the ferrite. The non-metallic inclusions are similar to those in Nos. 3, 4 and 6.
6	IVI.	0·07				Phosphorus ·053	99·70		Ferrite grains with a few pearlitic grains, the latter varying from the lamellar to the spheroidal type, with occasionally little grains of free cementite in the ferrite grain boundaries. The non-metallic inclusions are similar in number, size and appearance to those in specimens Nos. 3, 4 and 5.
7		3·46							The structure of this specimen is typical of grey cast iron, the groundmass consisting of fine lamellar pearlite in which are coarse curly plates or rods of graphite. There are occasional areas in which the graphite is more abundant than elsewhere. In these areas there is free ferrite.
8 and 9	II. and I	Steel and Platinum united by welding.							In these specimens only the steel was etched and examined. The structure of the steel was that of a 0·8/0·85 per cent. carbon steel and consisted solely of pearlite, chiefly in the finely lamellar condition, with a little granular pearlite. The welding has been very effective where the surface of the steel has been cleaned. In certain places the steel shows decarbonisation, and there is a small amount of scoria in the weld. Occasionally the platinum shows parallel cracks close to the welds, but the steel is free from these defects.
10	III.	Faraday's specimen made to imitate Damascene steel. 0·33	Si. 0·22			Phosphorus 0·10,	98·70	Fig. 5	The specimen was polished and examined on one of the long sides. Unetched, it showed numerous elongated slag inclusions. The structure developed by etching was of banded form and varied in different bands, some being martensitic, others troosto-martensitic, whilst some contained nodular troostite.

Representative Photomicrographs from the Further Nine Specimens.



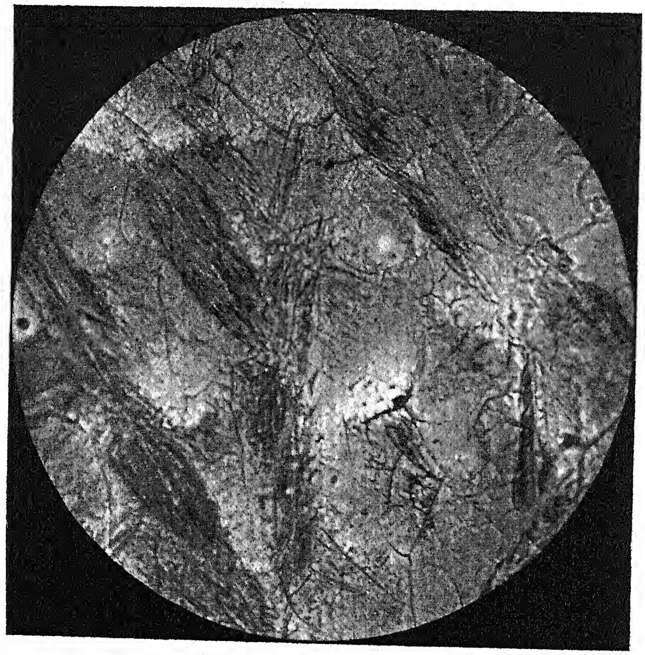
Specimen No. 2. (X. 500.)
C ·12. Rh 48·60 %.



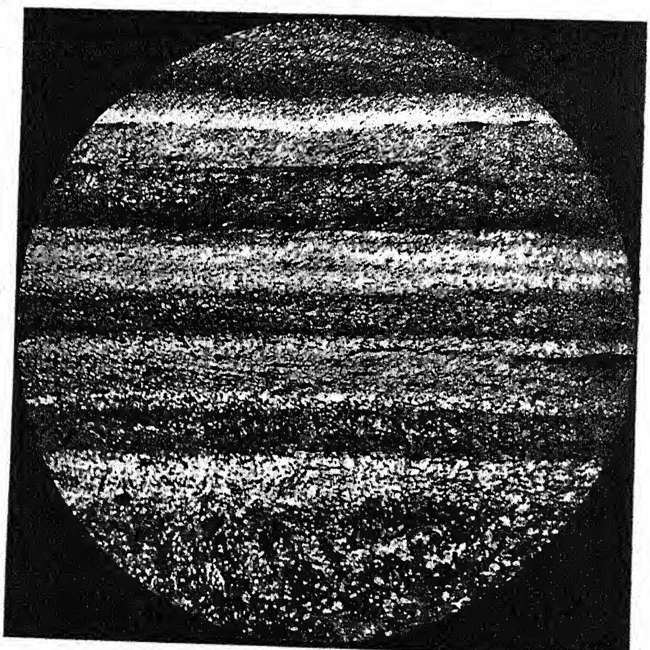
Specimen No. 3. (X. 250.)
C ·18. Pt 48·60 %.

[*To face p.* 232.

REPRESENTATIVE PHOTOMICROGRAPHS FROM THE FURTHER NINE SPECIMENS.



Specimen No. 4. (X. 500.)
C ·28. Pd 22·70 %.



Specimen No. 10. (X. 50.)
DAMASCENE STEEL

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materials. Its resistance to the ordinary form of atmospheric corrosion is also remarkably good, and although there are nowadays still better and less expensive alloys, Faraday had undoubtedly achieved in the present alloy a distinct advance; that is, a material considerably cheaper than the precious metals, while sacrificing only a little of their non-corrodibility.

Another special feature of this high percentage rhodium alloy is the high value of its specific magnetism, practically the same, in fact slightly greater than that of pure iron. This result is so extraordinary as to require confirmation by tests on specimens specially prepared and more suitable for magnetic testing.

This alloy does not possess any special property in the way of resistance to oxidation at high temperatures.

The duplex character of the microstructure is somewhat difficult to interpret in the presence of carbon, which, though very small in amount, is visible as a distinct constituent. It is possible that the darker portions seen in the photomicrograph shown in Plate LI, probably the first ever made of such a composition, differ from the lighter grains which are not etched by aqua regia, merely in their concentration of carbon.

It is more probable, however, that these represent a true duplex constitution, with the formation of inter-metallic compounds of rhodium and iron.

No. 3 (0·18 *per cent. C.*, 48·60 *per cent. Pt*).—This specimen forms an excellent parallel with No. 2, in which instead of platinum, there is a similar percentage of rhodium, both having low carbon.

The Brinell hardness (305–340) of this platinum alloy is slightly lower, and it was not quite so difficult to drill, although showing the same characteristic of glazing under the action of the drill.

The figure 9·83 obtained for the specific gravity is somewhat lower than the true value, the drill hole having disclosed some internal cavities. A further determination made on the drilled specimen after heating to 750° C. for fifteen minutes, the microstructure remaining practically unaltered, gave 10·75. The calculated specific gravity, taking iron as 7·82 and platinum as 21·50, is 14·45. As in the case of the rhodium alloy, there has therefore been a volume expansion on alloying, which calculation in this case shows to be as much as 34 per cent. It seems probable that drilling had not opened all the internal cavities, the specific gravity figure of 10·75 on which the calculation of expansion was based being thus still too low.

Faraday gives the specific gravity of the alloy with equal parts

of steel and platinum as 9·862, showing his accuracy of examination now checked some 110 years later.

The remarks made with regard to the resistance to corrosion and heat scaling of the rhodium alloy No. 2 apply generally to the present specimen, though to a less degree. That is, the addition of platinum is not so effective as that of rhodium.

The microstructure of this alloy seen in Plate LI is in distinct contrast to that of No. 2 (Plate LI), having a simple structure of grains, each subdivided into smaller grains, with carbide in the grain junctions. There is no indication here of a true duplex structure.

No. 4 (0·28 *per cent. C.,* 0·80 *per cent. Cu,* 22·70 *per cent. Pd*).—The presence of copper in this alloy to the amount of 0·80 per cent. is somewhat difficult to account for. It would hardly seem to represent a deliberate addition, since no important effects are to be expected from it in view of the much larger percentage, 22·70, of palladium present. It seems equally improbable that copper, except in a much smaller percentage, could be added accidentally, even as an impurity in the constituents of the mixture. In studying the results, however, due account has been taken of its presence.

The hardness of the alloy, 386–392, constitutes a still further example of comparatively high hardness in alloys of iron with elements which are themselves not specially hard. The hardness of palladium is about 60.

The calculated specific gravity of the alloy, taking palladium as 12·0, is 8·728, which, when related to the actual specific gravity, 8·22, indicates a volume expansion on alloying of 6·2 per cent.

Palladium, in contrast with rhodium and platinum, it is clear, does not confer resistance to acids, except against hydrochloric acid, or to atmospheric corrosion, though it is similar in its absence of a material influence on the resistance of steel to heat scaling. As with the high percentage rhodium alloy No. 2, this palladium alloy appears to have an extraordinarily high specific magnetism, a fact which should, however, be confirmed by tests on specially prepared specimens more suitable for a magnetic test.

The microstructure (Plate LII) is also quite different from that of the alloys of platinum and rhodium, although some reservation is necessary on this point owing to differences in the percentage compositions.

No. 5 (0·11 *per cent. C.,* 1·25 *per cent. Rh*).—The interest in this alloy is somewhat less than it would otherwise have been, since among the seventy-nine specimens in the earlier research were three with a similar small percentage of rhodium. All the latter

were, however, high in carbon (0·92 per cent. to 1·35 per cent.). Close comparison of their characteristics is not possible as they were in the forged, not in the cast, condition, as the specimens now described.

The rather high figure of 0·106 per cent. for phosphorus in the present specimen is a clear indication that wrought iron has been used as the base.

The peculiar pattern on the upper surface of this specimen is to be noted, but in the absence of any reference by Faraday to attempts by him to produce patterns on his ingots, nothing of definite nature can be said further on this point.

No. 6. " *Pure Iron Fused.*"—The special interest in this specimen is that it still further demonstrates Faraday's skill in melting unalloyed iron, providing an excellent standard test in this respect. This " pure iron," with its low figure of 0·053 per cent. phosphorus, confirms that in this case Faraday employed iron which was certainly purer than the base used in making the majority of his low carbon alloys. However low the carbon may have been in this purer iron, Faraday has undoubtedly added to it little or nothing in his melting operation, as shown by the very low figure, namely, 0·07 per cent., in his melted product, representing undoubtedly a metallurgical feat at the time he made these experiemts, 1819–1824, and seeing the comparatively crude equipment with which he did the work. Only those who have to handle " iron," that is to say, 99·95 per cent., in the molten condition know how difficult this is. It is true the modern high-frequency furnace overcomes some of these difficulties, but not all, because of the avidity with which such iron absorbs gas.

No. 7. " *Crystalline Carburet of Iron.*"—If this specimen represents, as the author feels it does, Faraday's famous " crystalline carburet of iron," it is an important specimen. Further tests are in hand.

This product was highly regarded in a special article appearing about that time in the *Proceedings of the Société d'Encouragement pour l'Industrie Nationale*, Paris. In their *Bulletin*, Vingtième Année (No. CCX), December, 1821, it is stated that " Messrs. Stodart and Faraday have given us the first analysis of Wootz, and to whom we equally owe our knowledge of alloy steels and notably of the combination of steel and of a carburet of iron."

Faraday also dealt with this subject fully in his important letter to Professor Gaspard de la Rive at Geneva, dated June 26th, 1820, as shown on p. 122 of this book.

Nos. 8 *and* 9. "*Platinum and Steel Welded.*"—The effectiveness of the welding has been confirmed by the micro examination, the steel used proving to be about 0·8 per cent. carbon. There is no evidence of actual alloying of the platinum and steel at any appreciable distance from the welds.

No. 10. "*Attempt to Imitate Damask.*"—It was hoped that the micro examination might disclose some evidence as to the method by which this specimen had been produced. There were, however, no inclusions which could be identified as alumina or titanium nitride. These where present in steel have quite characteristic and recognisable forms. The inclusions in the present specimen, amounting approximately to 0·20 per cent., as seen under the microscope, are in fact of the type usually met with in wrought iron, and consist of slag and iron oxides. Analysis also failed to detect the presence of either aluminium or titanium.

That the specimen has been twisted and forged is clearly visible in the macrostructure, that is, the visual examination of the etched surface. Naturally the bands shown in the photomicrograph (Plate LII) appear almost straight, since they only represent a very short length. It would seem possible that the method adopted to produce this particular specimen was in the first place to weld together under the hammer carburised strips, then to twist them afterwards, forging the piece flat.

The total number of tests, chemical, physical and mechanical, carried out in this particular research, amounted to 133. Full particulars are given in the following Table XXIV.

Table XXIV

Number of the Various Tests Carried Out on the Nine Further "Steel and Alloys" Specimens made by Faraday and referred to in his Diary, period November 3rd, 1823, to June 28th, 1824.

Chemical analyses	36
Micrographic examination (including 5 photomicrographs)	9
Specific gravity	10
Hardness tests	39
Magnetic tests	6
Corrosion tests	30
Heat scaling tests	3
	133

Conclusions Regarding the Later Specimens.—The link which the present research has established between these specimens and

Faraday's records should certainly increase their historic value and interest, while it is hoped also that the metallurgical examination which the author has been able to make will have given some further insight into their character than was possible by the methods available to Faraday.

From the record mentioned, it would appear that Faraday attached importance to the present collection, probably as representing some of the most interesting results of his labours in the field of "steel and alloys." The completeness of the original collection has, it is true, been disturbed in the course of time, but of the nine original specimens seven remain, with the compensating addition of an interesting high percentage alloy of iron with palladium.

In the high percentage alloys of iron with platinum and rhodium Faraday had apparently progressed some way towards one of his desired objectives, namely, an untarnishable alloy. These alloys possess some merits, too, as regards resistance to acids.

Alloys of iron and steel with eight of the metallic elements with which Faraday states he experimented have now been found among the specimens made by him and still in existence, namely, copper, chromium, gold, nickel, palladium, platinum, rhodium and silver. Only the alloys of iridium, osmium, tin and titanium remain to be found, and it now hardly seems probable these will be discovered. As regards titanium, Faraday stated in his paper that all his attempts to alloy it with iron had proved unsuccessful. Since also iridium and osmium were not separately available to Faraday, but only in the form of the alloy osmium-iridium, the number of the ferrous alloys unrepresented is really reduced to two, namely, those with osmium-iridium and with tin.

Naturally the alloys actually found and examined in the two researches do not form complete series of increasing percentage for all the alloying metals, and such merits as, for example, the platinum and rhodium alloys may possess can only be fully investigated by the preparation of complete series. The indication is that an investigation might prove of special interest to metallurgical science, and possibly repay the time expended in such a research.

Examination of Some Century-Old Razors, and a Razor made from Faraday Steel

The razors shown in Plate LIII and forming the subject of this section comprise, besides the one E prepared by the author, as

already described, from Specimen No. 15/C.1-4 in the Faraday collection, four others of a specially interesting character obtained from various sources. These are as follows :—

(A) The razor marked VR and "Concave Razor Silver Steel," one of a pair purchased by the author from the collection of Mr. George H. Gabb.

(B) A razor made by Mr. W. H. Pepys, F.R.S. (1775—1858), and bearing his mark. The blade of this razor formed part of the collection already referred to, and placed by the kindness of the Royal Institution at the disposal of the author for examination. This collection comprised seven specimens illustrating stages in the preparation of a razor, the present specimen representing the finishing stage, that is, after a second buff polishing. The handle in this case is a modern one fitted by the author, to enable the razor to be tested in use.

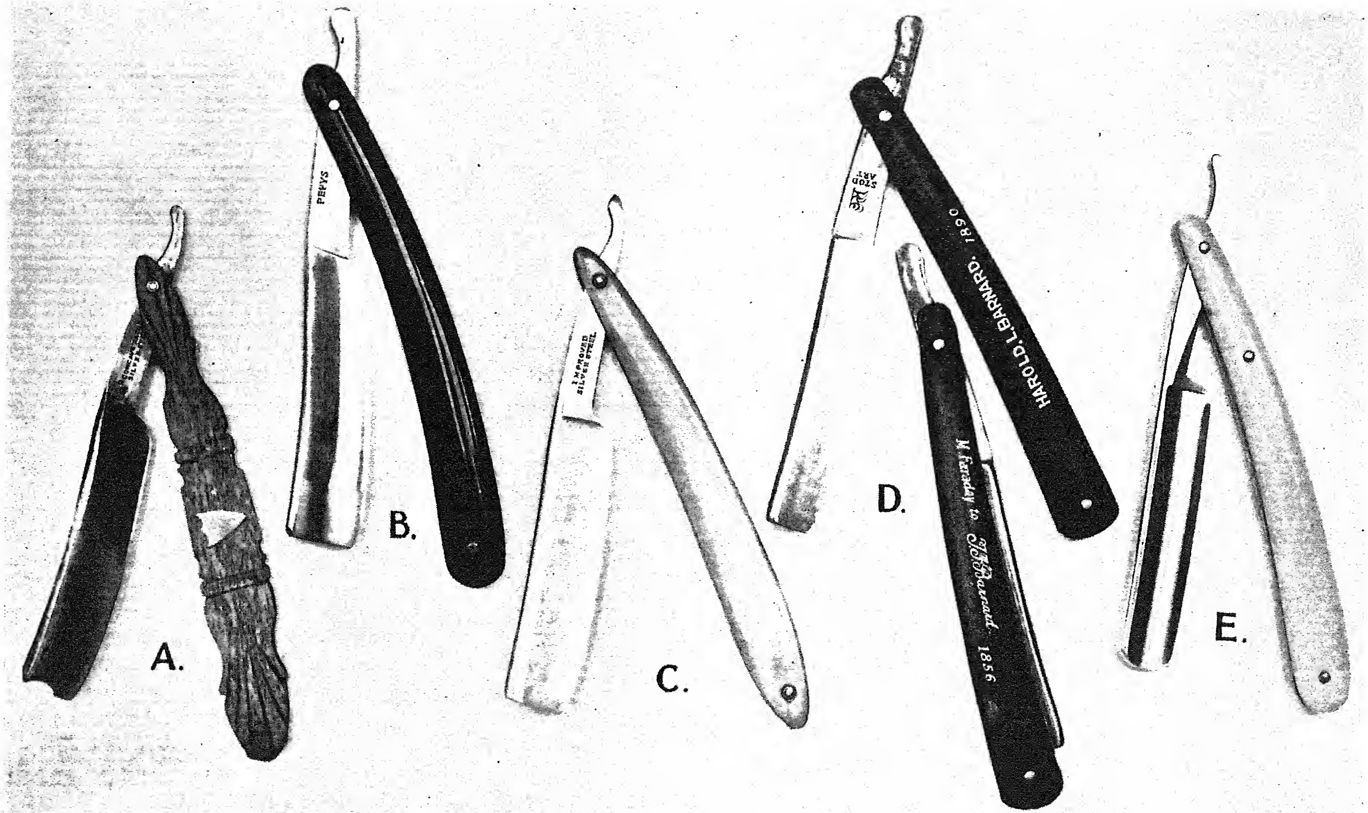
(C) Razor marked "Improved Silver Steel" and fitted with an ivory handle. This razor, which belonged to Faraday, was kindly loaned by Mr. A. Evelyn Barnard, with permission to make such examination as might be considered useful.

(D) This razor is particularly important, since besides the inscription on the handle, showing that it had actually belonged to Faraday and was given by him to his nephew, Mr. James Faraday Barnard, it bears the mark indicating it to have been made by Stodart, and also the Indian sign shown enlarged in Fig. 12, indicating wootz steel. Moreover, it contained 1·10 per cent. of platinum. Thus four important points of information are concentrated in this particularly interesting and valuable article of Faraday's steel.

For the purpose of comparison, a modern razor made by a well-known Sheffield firm was included. This is referred to under the letter F.

Naturally, the most interesting feature to be ascertained regarding these razors was their chemical composition, and although the amount of material which could be obtained for this purpose was strictly circumscribed, at any rate in the case of specimens C and D, by the necessity for avoiding any means of a destructive character, it was found possible to obtain a few grams in each case in the form of drillings taken from the unhardened portion of the steel at the end of the tang. In the case of the Pepys razor there was available in the collection referred to a specimen representing the rough blank from which this razor had been prepared. Consequently the very complete analysis which was made on a sample

CENTURY-OLD RAZORS EXAMINED BY THE AUTHOR. ALSO RAZOR PREPARED BY THE AUTHOR FROM STEEL MADE BY FARADAY.



A. Razor believed to have been made by Stodart, and bearing the marks $\frac{\text{♔}}{\text{VR}}$ and "Concave Razor, Silver Steel."
B. Razor made by Pepys. The handle is a modern one fitted by the author.
C. Razor marked "Improved Silver Steel" which belonged to Faraday.
D. The "Faraday-Stodart-Barnard-Indian Wootz steel" razor fully described on pp. 238 to 242.
E. Razor prepared by the author from steel made by Faraday and containing 0·69 per cent. of Platinum.

It should be noted that Figs. C. and D. represent the razors actually used by Faraday.

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taken from this blank may reasonably be expected to represent that of the razor itself, which, in consequence, it was not necessary to drill.

With the small amount of sample obtained from razors A, C and D the author was enabled to carry out a limited analysis, which, however, was sufficiently complete to ensure against the possibility of an appreciable percentage of any element remaining undetected. The whole of the analyses are given in Table XXV, together with those of razors E and F prepared by the author from Faraday's steel.

The most striking discovery made as the result of these analyses is the presence of 1·10 per cent. platinum in the razor D, which beyond doubt therefore is one prepared by Stodart for Faraday from steel made by the latter. This discovery is further gratifying to the author as justifying his selection of steels containing approximately the same carbon and platinum percentages for the preparation of a razor and knives. The existence of this razor specimen D of which the author was entirely unaware at the time the small knives and razor mentioned in this section were made, shows that Faraday's expectation of, or belief in, his ability to improve cutlery by alloying additions could best be achieved by this comparatively small percentage of platinum. The small amount of sample available was inadequate to determine chemically anything very positive regarding the real significance of the wootz sign, that is, as to whether any of the non-metallic constituents are present which Faraday found to be characteristic of wootz steel. From the analyses made no special features presented themselves to indicate anything special in this steel. A micro examination also made did not disclose any abnormal results in the form of inclusions.

Specimens A and C, which may be conveniently referred to together, although described as being of silver steel, do not contain any proportion of silver sufficient to be detectable by analysis in the small samples available. If any is present it probably cannot amount to more than 0·10 per cent. in either case, from which it would appear that no appreciable amount of silver has actually been added. The examination also which was made of a micro section of razor A, did not disclose any inclusions of silver.

It will be noticed that in their carbon content these two razors differ very considerably, A containing only 0·85 per cent., although high enough to maintain a good cutting edge, while C has no less than 1·40 per cent.

TABLE XXV

ANALYSES AND HARDNESS DATA OF SOME CENTURY-OLD RAZORS, ALSO A RAZOR PREPARED BY THE AUTHOR FROM FARADAY'S STEEL.

Reference Letter.	Description.	Analysis.							Brinell Hardness.			
									Tang.		Blade.	
		C.	Si.	S.	P.	Mn.	Pt.	Fe.	End.	Near Blade.	Back.	Edge.
A.	" Concave Razor-Silver Steel " believed to have been made by Stodart.	·85				·02		99·00	250/290	610	398/435	610/622
B.	Razor made by Pepys.	1·18	·12	·026	·022	·07		98·30	235/265	245	586/622	628/635
C.	" Improved Silver Steel " Razor which belonged to Faraday.	1·40				·04		98·30	280/305	650/660	430/450	605
D.	Stodart Razor with Indian sign for Wootz. Belonged to Faraday.	·84				·05	1·10	97·80	310/320	600/650	530	520/575
E.	Razor made from Faraday Steel specimen 15/C. 1-4.	·94	·30				·69	98·30	298/343	591/622	552	622/652
	FOR COMPARISON :—											
F.	Modern Razor.	1·40				·09		98·30	320/370	634/640	622/640	600/640

The full analysis of the Pepys razor B shows it to be of plain carbon steel of good quality, such as might have been used for the best razors at any time since it was made. Naturally, in this case there was nothing in the circumstances to expect that any special elements had been incorporated, the razor apparently representing good current practice as carried out at that time.

Hardness tests were made with the diamond pyramid on one face of the blade of each of the razors. A position was chosen as near the edge as possible, usually within 0·1 inch, and also near the back, the tests being made in this way at both ends of the blade. Tests were also made along the tang. The hardness figures obtained are shown in Table XXV.

No features of special significance appear in these data. The razor D is not quite so hard towards the edge as the others, but this is clearly due to its heat treatment and not to its special composition, since steel of this composition, that is, containing an approximately similar amount of carbon and platinum, has shown itself, both in razor E and in the miniature knives, capable of being fully hardened.

It will be appreciated that to make a fair comparison of the practical merits of these razors provided something of a problem, because of their variety of pattern and as apart from quality the pattern of razor which is suitable to one individual is unsuited to another.

This being recognised, an attempt was made to test the razors under as comparative conditions as possible in the following way.

After they had all been whetted by the same skilled man each razor was used once by the same member of the author's research staff, chosen as being a difficult subject, that is, having a stiff beard, and a careful note taken of its actual performance. Before and after the test, examination of the edge was made under a low-power microscope.

A note of the behaviour in whetting was taken, and this showed that razors B and C were rather harder than the other three, which could be classed more or less together. From an inspection of the analyses in Table XXV. it is apparent that the carbon percentage, which is highest in the first two mentioned, was the principal factor in determining this behaviour.

Razors B, made by Pepys; A, believed to have been made by Stodart and described as "silver steel"; D, made by Stodart from Faraday's platinum steel; and E, the razor prepared by the author from Faraday's platinum steel, all came successfully through this test. They were classed in this order of merit both

as regards the manner in which the edge was maintained during the test and in its appearance under the microscope after use. It was, in fact, found possible to use B, A, and D successfully a second time without stropping.

With regard to C, the "improved silver steel" razor belonging to Faraday, this failed to maintain its edge during the test, examination under the microscope showing that tiny portions had broken out, leaving a saw-like edge.

The modern razor F was used four times in succession without stropping before its edge became appreciably dulled.

When further tested by another member of the staff each of the razors A to F behaved in quite a satisfactory way, little distinction being found in their cutting qualities, preference being determined rather by the suitability of form of the razors as regards convenience of handling.

It can reasonably be concluded from these tests that the addition of platinum in comparatively small percentages does not appear to improve the cutting properties of hardened carbon steel. On the other hand, Faraday gave away quite a number of similar platinum steel razors, which it is understood gave satisfaction to the users. For example, one was presented by him to the late Professor John Tyndall, F.R.S., and quite recently the author saw Mrs. Tyndall, who remembered the razor, but efforts most kindly made by her to find it were not successful.

Total Number of the Tests carried out in the whole of the Research.— In concluding the description of this research it may be of interest to present a summing up of the whole of the work done. The total number of tests carried out on the whole series of specimens examined, including the seventy-nine specimens dealt with in the first research, the further nine specimens from the Science Museum, and finally the six razors and one miniature knife examined. The full information giving the weights, number of chemical analyses carried out and tests made is given in the following summary :—

(A) Weight of the eighty-eight specimens :

	Grams	lbs	ozs.
Weight before the research . . .	3741·28	8	$3\frac{3}{4}$
Weight remaining after the research .	3159·36	6	$15\frac{1}{4}$
Difference	581·92	1	$4\frac{1}{2}$
Amount used from the razors .	9·31		$\frac{1}{4}$
Total amount used in the whole research	591·23	1	$4\frac{3}{4}$

(B) Number of chemical analyses 493

(C) Number of tests, chemical, physical and mechanical . 866

CHAPTER VIII

APPRECIATION OF FARADAY'S WORK

Diversity of Opinions

On many occasions in the past the author has referred to Faraday's pioneering work in regard to his researches on alloys of iron and steel with various elements. Nevertheless, it was not until he had the opportunity of subjecting specimens of the Faraday alloys to complete examination that he realised the full importance of the work that had been done in the basement laboratory of the Royal Institution more than a century ago. Like many others the author had previously regarded Faraday's work in this field as a brief but interesting experimental attempt made at an early date and had not recognised that the research was one which had extended over a period of about six years. However, almost immediately after commencing the present research on Faraday's specimens it became evident that these were of real importance as regards establishing Faraday's priority in the domain of research on alloy steels. It became apparent that much interesting information was to be obtained from these specimens and, above all, it became clear that there was no justification for the sweeping assertion that Faraday's work on alloy steels " ended in nothing," as was stated by one of his biographers, Dr. Bence Jones, F.R.S.

As a matter of interest, the author has collected a number of opinions and comments relating to this question, and these are reproduced now. Taking these opinions in conjunction with the information presented in the present book, the reader will doubtless agree that Faraday's work was of real and lasting interest and value. In fairness to those who have dismissed it too lightly, it must be said that the author alone has had the opportunity of subjecting the specimens to complete examination, without which no true judgment of their properties and importance could possibly be formed.

Unfavourable Opinions

Perhaps the most widely known and generally accepted of the opinions hitherto expressed concerning Faraday's work on steel and alloys is that given by his biographer and personal friend, Dr. Bence Jones, F.R.S., who, in his obituary notice of Faraday

in the Royal Society Proceedings, says: "In 1822 a paper, 'On the Alloys of Steel,' by Stodart and Faraday, was read to the Royal Society and printed in the Transactions. . . . The results of the paper on Steel were of no practical value, and this, one of his first and most laborious investigations, is strikingly distinguished from all his other works by ending in nothing." For some reason, no reference is made by Bence Jones to the first paper contributed by Stodart and Faraday to the Royal Institution in 1820, namely, "Experiments on the Alloys of Steel, made with a View to its Improvement," a most informative and interesting contribution.

In his famous book, *Life and Letters of Faraday*, Vol. I., p. 326, Bence Jones says: "Green, Pickslay & Co., in Sheffield, for a time used the alloy of steel and silver for fenders, etc., and the alloys of steel and rhodium, iridium and silver, they made into razors; but this long and difficult piece of work proved of no lasting use."

Thus, in two separate places, tribute is paid by him to the laborious nature of Faraday's work on steel and alloys, yet he says that it "ended in nothing" and was of "no lasting use." For reasons fully explained in this book, the author asserts that Faraday's work was of real importance and it may well be found that the information obtained as an outcome of the present research on such of the alloys made by Faraday as have become available will lead and inspire further developments in alloy steels.

Curiously enough, Bence Jones says, in another part of his obituary notice of Faraday in the Royal Society Proceedings, when speaking of Faraday at the age of thirty-eight years (1830): "If Faraday's scientific life had ended here it might well have been called a noble success. He had made two leading discoveries, the one on electro-magnetic motions, the other on the condensation of several gases into liquids. He had carried out two important and most laborious investigations on the alloys of steel and on the manufacture of optical glass." The reference to the research on alloys of steel is here favourable rather than unfavourable and certainly does not convey the impression given by the other passages quoted above.

In fairness to this biographer it must be pointed out that he was not a metallurgist, and only a metallurgist, armed, too, with the wider knowledge and better facilities now available, could fully appreciate the importance of Faraday's work and the remarkable measure of success he attained with very limited resources. If Bence Jones had been a metallurgist and could have seen the results now published in this book he would not, we may be sure, have spoken of his friend's laborious investigations ending in nothing.

Another comment of similar nature on Faraday's research concerning steel and alloys is to be found in Professor A. A. de la Rive's "Memoir of Michael Faraday: His Life and Works," published in *Phil. Magazine*, Vol. XXXIV., December, 1867, shortly after Faraday's decease, where this distinguished scientist says: "Although interesting in many respects, the results which Faraday obtained in his great investigation of the alloys of steel were not proportionate in their importance to the time and trouble which they cost him." Concerning this the author can only say that he disagrees entirely, and that in his opinion Faraday did extraordinarily well to accomplish so much in the course of a few years, specially in view of the fact that at the time he was engaged on so many other researches and seeing the somewhat imperfect nature of the experimental apparatus with which he often had to work.

In his well-known book, *Michael Faraday, His Life and Work*, the late Professor Silvanus P. Thompson adds to the unfavourable comments on Faraday's steel researches by saying that the various alloys which Faraday made were of no great practical use. This assertion is perhaps justifiable so far as immediate and lasting practical applications were concerned, but if Professor Thompson had been a metallurgist specially concerned with steel, and if he had had the privilege of subjecting Faraday's specimens to complete examination, he would no doubt have added that although Faraday's work may not have had any immediate and lasting practical consequences it was of great significance and represented a wonderful research, notably in relation to later developments. Even though he did not do this, Professor Thompson paid a tribute to one very important aspect of Faraday's research, for he said, "the research demonstrated the surprising effects which minute quantities of other metals may have upon the quality of the steel." Surely, if it accomplished nothing more than this, the research was well worth while. Actually the outstanding merit and importance of Faraday's researches on steel lie in the fact that these were the first systematic investigations of a most suggestive character in regard to an extensive range of alloys of steel with different elements, and they demonstrated the remarkable effects which may be produced by minute, also larger, quantities of other metals alloyed with steel. These are foundation stones on which our increasing knowledge and use of alloy steels have been built.

Evidence from Faraday's Papers

In the case of a man of such keen observation, sound judgment and sterling character as Faraday, we may safely take his own

statements as being entirely honest and accurately in accordance with the state of knowledge and practice at the time when they were made. Taken on this basis, the papers by Stodart and Faraday of 1820 and 1822 afford much evidence that the researches on steel and alloys were by no means a disappointment to Faraday. This will be seen from the quotations and notes in Chapter VI., and yet more clearly by reference to the full text of the papers.

Consider, for example, the opening words of the Royal Society paper, of 1822 : " The alloys of steel made on a small scale in the laboratory of the Royal Institution proving to be good, and the experiments having excited a very considerable degree of interest both at home and abroad, gave encouragement to attempt the work on a more extended scale ; and we have now the pleasure of stating, that alloys similar to those made in the Royal Institution have been made for the purpose of manufacture ; and that they prove to be, in point of excellence, in every respect equal, if not superior, to the smaller productions of the laboratory." We may be sure that Faraday would never have permitted such words to be published under his name if he had not been fully convinced that the alloys he had discovered were a real advance in the desired direction, and, naturally Stodart, who from practical knowledge was well informed about steel, its applications and treatment, evidently shared in these same views. Further contemporary evidence on this point is mentioned below.

The truth of the matter is that Faraday was undoubtedly far ahead of his time in regard to his steel researches. The state of knowledge and practice in the iron and steel industry offered no opportunity for a favourable reception of his ideas and discoveries, and the state of the engineering and manufacturing industries offered but little demand and scope for the use of alloy steels. Nevertheless, had circumstances permitted Faraday to continue his work on steels and if, in particular, he had been able to work at Sheffield in direct touch with steelmakers there is little doubt that his discoveries would have continued and borne much fruit. The extent to which he was out of touch with the steelmakers—owing to distance and, probably, the effects of secrecy and conservatism on the part of the steelmakers—is revealed by the opening sentence of the following paragraph (" On the Alloys of Steel," by Stodart and Faraday, *Phil. Trans.*, 1822) :—

" We are not informed to what extent these alloys, or any of them, have been made at home, or to what uses they have been applied ; their more general introduction in the manufacture of cutlery would

assuredly add to the value, and consequently to the extension of that branch of trade. There are various other important uses to which the alloys of steel may advantageously be applied. If our information be correct, the alloy of silver, as well as that of platinum, has been to some considerable extent in use at His Majesty's mint. We do know, that several of the alloys have been diligently and successfully made on the Continent, very good specimens of some of them having been handed to us; and we are proud of these testimonies of the utility of our endeavours."

These words reveal a firm conviction that steel alloys were of real importance, and that the research which led to their discovery had been useful.

As judged by the standards of those days, Faraday's results were remarkable and ought certainly to have been followed up; as judged by the standards of to-day, they represent the true beginning of research on special alloy steels.

Further Contemporary Evidence

An interesting confirmation of certain claims advanced in the paper which Stodart and Faraday presented to the Royal Society in 1822 is to be found in the *Edinburgh Philosophical Journal* for April-October, 1822, Vol. VII., p. 350, where the editor states: "Mr. Stodart was so obliging as to favour us with specimens of several of these alloys for optical purposes, and though various plates of polished steel kept beside them for more than a year, were all affected with rust, yet not one of the alloys have suffered the least change." The alloys here mentioned were evidently products of the later experiments at the Royal Institution and not from material made "in the large way" at Sheffield. In any case it must be remembered that these specimens represented only a small number of the total made by Faraday, and there is no reason to doubt that the above testimony was honest and accurate as regards the actual specimens tested by the editor of the journal in question. It must also be borne in mind that the results obtained from steel extra well polished, carefully kept and not exposed to severe atmospheric influences might well deceive an ordinary observer unacquainted with the behaviour of iron and steel as regards its resistance to corrosion.

The letters from the Sheffield firm of Green, Pickslay & Co. to Faraday reproduced on p. 133 also bear every indication of honest belief and confidence that some of Faraday's alloys were superior to the steel hitherto available.

Other Favourable Opinions

Coming to more recent times, a significant tribute to the value of Faraday's work on steel alloys is to be found in the article on Faraday in the *Dictionary of National Biography*, by Professor John Tyndall, F.R.S., who says, " . . . jointly with Mr. Stodart, he worked with success on the alloys of steel. A razor made of one of these alloys and presented to the present writer by Faraday himself, is still in his possession." Unfortunately, all attempts to trace this historic razor have failed, but Tyndall's reference to it and his assertion that Faraday "worked with success on the alloys of steel" bear out the author's contention that Faraday's research by no means "ended in nothing."

In the course of an address on "The Chemical Works of Faraday in Relation to Modern Science," delivered at the Faraday Centenary Meeting of the Royal Institution on June 26th, 1891, Professor, afterwards Sir, James Dewar, F.R.S., pointed out that part of Faraday's early and important work was an investigation into the properties and combinations of steel with other metals, demonstrating that in certain cases an admixture of small proportions of such metals as silver and other elements brought about a very considerable change in the character of the product.

Similarly, in the course of a Royal Institution lecture on "The Rarer Metals and Their Alloys," delivered on March 15th, 1895, Sir William Roberts-Austen, pleading for further research as to the effect of rarer metals on the commoner ones, said :—

> "We must go back to the traditions of Faraday, who was the first to investigate the influence of the rarer metals upon iron, and to prepare the nickel-iron series of which so much has since been heard. He did not despise research which might possibly tend to useful result, but joyously records his satisfaction at the fact that a generous gift from Wollaston of certain of the 'scarce and more valuable metals' enabled him to transfer his experiments from the laboratory at Albemarle Street to the works of a manufacturer at Sheffield. Faraday not only began the research I am pleading for to-night, but he gave us the germ of the dynamo, by the aid of which, as we have seen, the rarer metals may be isolated."

These words pay a well-merited tribute to Faraday's work and, as regards the remarks on the nickel-iron series, Roberts-Austen was quite correct. Nickel steel had been made by Nature in meteorites, but Faraday was the first to investigate that series which has since proved to be of such great importance.

In that interesting book, *Roberts-Austen : A Record of His Work*, by Sydney W. Smith, the following paragraphs appear :—

"1820 : The first quarter of the century did not draw to an uneventful close, for Faraday, working with Stodart, an eminently practical man, gave (in 1820) a stimulus to the study of alloys, and produced the first specimen of nickel steel."

"1822 : In the year 1822 Faraday pointed to a fundamental difference between hard and soft steel, the latter yielding a 'carburet of iron' when treated with hydrochloric acid, while hardened steel dissolves completely."

Here again we have recognition of another valuable part of Faraday's metallurgical work, that is, when he proved the existence of a compound of iron known as the Carburet, or, as now expressed, Carbide of Iron. This discovery as well as Faraday's work relating to steel and alloys quickly received full and generous recognition from the scientists in France, as expressed in the remarks quoted below, which appeared in 1821 in the Proceedings of the Société d'Encouragement pour l'Industrie Nationale. The work of this society was of great importance and value in those early times, and its existence to-day shows that this continues to be so. In order to emphasise the importance of certain expressions in the following quotations these are placed in italic type :—

"Dans les séances des 13 juin et 11 juillet 1821, M. Merimée a entretenu le Conseil du travail commencé par la commission chargée du répéter et de continuer les expériences *commencées en Angleterre* sur l'amélioration de l'acier par son alliage avec différentes substances."

"MM. Stodart et Faraday, par leurs *belles expériences* sur les alliages de l'acier, ont donné à sa fabrication la même impulsion qu'à différentes époques du siècle dernier lui donnerent succivement Réaumur, Tobern-Bergmann, Swendenborg, Scheele, Meyer, Swan-Rinmann, Peret, et ensuite nos chimistes français Vandermonde, Monge, Berthollet, Pelletier, Guyton-Morveau, Vauquelin et Clouet."

"*C'est à MM. Stodart et Faraday*, qui nous ont donné la première analyse de wootz, *que nous devons également la connaissance des aciers d'alliage*, et *notamment* de la *combinaison* de *l'acier et d'un carbure de fer*."

Another important acknowledgment from quite a different source has recently come before the author's notice, namely, certain statements by the Russian metallurgist now residing in London, Colonel N. T. Belaiew, C.B. His remarkable work in metallography and other branches of metallurgy is well known. During the discussion on the author's paper on "The Development of Alloy Steels," read at the Empire Mining and Metallurgical

Congress, held at the Wembley Exhibition in 1924, Colonel Belaiew stated :—

"The work of Stodart and Faraday had a very wide repercussion in many countries outside their own, and if some of the contemporaneous metallurgical papers in other countries, and more particularly in his own country, Russia, were consulted, it would be realised how important that work had been regarded, as about 1820 in Russia, for instance, the work of Stodart and Faraday gave rise to the whole range of experiments made by Anossoff. Anossoff tried to explain the properties of carbon steels on the assumption that carbon steel was an alloy steel, and he first set to work by repeating the experiments of Stodart and Faraday, and only by degrees did he come to the conclusion that carbon steels were not alloy steels, but that their properties were to be ascribed to carbon."

Finally, some words of Sir William J. Pope, F.R.S., may be quoted from his article on "Faraday as a Chemist," in the jubilee number of the *Journal of the Society of Chemical Industry*. In the course of a survey of Faraday's activities, Sir William says :—

"Whilst this work was in progress Faraday was engaged in an investigation of the alloys of steel in conjunction with James Stodart; this had for its object the improvement of steel intended for the manufacture of cutting instruments and the diminution of the tendency to rust.

"A large number of new alloys were prepared and studied: some, such as those with platinum, had little tendency to rust; those with rhodium could be forged and tempered, and the silver-steel alloys were used for some time for the manufacture of such articles as fenders.

"Although Faraday occasionally presented his friends with razors forged from certain of his new alloys, the work found no considerable technical applications.

"The modern extensive use of nickel-steel and chromium-steel, both of which Faraday prepared, suggests that the work was in advance of the needs of the times."

As regards these words, the author is of the opinion that one of the chief reasons why Faraday's work found no considerable and immediate technical applications was that it was far in advance of the needs of the times.

The Author's Conclusions

In the light of his own fifty years of experience in the field of ferrous metallurgy, largely concerned with alloy steels during the whole of this period, the author maintains that the steel alloys produced by Faraday more than a century ago constituted another proof of his genius and foresight. They remain of great interest and importance even to-day, and they represent a research which was certainly no failure, but rather a column built well and firmly

as far as it went and then abandoned by its builder and others for reasons not now known, when it might have been continued as it was later by others and carried to such a successful issue. Failure, as judged by the lack of continued practical application and development, lay not in Faraday's conception and research, but in the fact that his work was in advance of the times, was not continued by others when he laid it aside, and that the possibilities were not appreciated by practical men.

The adverse or slighting comments on Faraday's work contained in the unfavourable opinions quoted can only be attributed to the fact that those who made them based their judgment on the argument that because Faraday's steel alloys were not to a large extent used industrially they were therefore a failure. Those who argued thus, consciously or unconsciously, failed entirely to see the enormous importance of this early research work by Faraday, and the extent to which he anticipated later workers by making systematic studies with some twenty elements and other substances added to iron.

The significance and value of Faraday's work on "steel and alloys" lay not in any immediate practical application of great importance, but in the later developments in this field. It is related that Faraday himself, when some inquiring person wanted to know, *à propos* of his discovery of induction movement by magnetism, what good all that was, retorted: "My dear sir, what is the good of a baby?" The simile is a happy one and entirely applicable to Faraday's work on alloys of steel. His planning and execution of an extensive and systematic investigation of alloys of steel with a large number of elements in a great variety of proportions was undoubtedly the "baby" which later grew into alloy steels as we know and use them to-day.

Not knowing the colossal amount of time, labour and money which would have to be expended, in a generation blessed with much better facilities, before alloy steels could be made really commercial products, Faraday himself was perhaps sometimes inclined to regard his researches in this field as a comparatively fruitless expenditure of several years of laborious toil. Actually, they were far from being this. His work pointed the way to the future development of alloy steels and even in the comparatively small number of specimens which have survived to the present day there was the germ of modern alloy steels—manganese steel, silicon steel, nickel steel, chromium steel, tungsten steel, ternary alloys such as nickel-chromium non-rusting and heat-resisting steels, high-speed tool steels, and later products such as an alloy

which the author recently examined, containing no fewer than nine elements, viz., carbon, manganese, chromium, nickel, tungsten, cobalt, vanadium, molybdenum and iron.

Without doubt, no one before Faraday—whether metallurgist, chemist, physicist or engineer—had ever experimented with so many elements in combination with iron. At that time, however, there was neither the same opportunity for continued research as there was later in the way of knowledge and resources nor the same spur to investigation in the shape of insistent demand for steels of special quality as regards mechanical strength, resistance to corrosion and other properties. In this sense Faraday's research was long before its time, but that adds to, rather than detracts from, the credit due to Faraday himself.

In the light of all the facts, including the results of the present investigation, it cannot be denied that his work was indeed a brilliant anticipation of similar labours by later metallurgists, and that it passes triumphantly the acid test of genuine and successful research—the search for and the discovery of fresh knowledge.

CHAPTER IX

LATER DEVELOPMENTS OF ALLOY STEELS

Definition of Terms

The conception which formerly ruled in regard to the term "alloy" prevails to this day in the mind of the general public. An alloy to many implies nothing more than the addition of a baser metal to a finer one, the object in mixing the two together often being to obtain a cheaper commercial article and one that will wear better. This is, of course, not at all the case in regard to the special steel alloys of the present day. The definition of the word "alloy" might better be made to read "the combining by fusion of two or more metals together, or of a metal with one or more metalloids, for various specific purposes." And this, by the way, is precisely what Faraday set out to do; his own words, setting forth the aim of his investigation, afford yet another proof of the clarity of his inspiration.

Uncertainty and confusion are often introduced into the terminology of ferrous metallurgy by the lack of any generally accepted definition of exactly what is meant by the word "steel" itself. In earlier days there was no doubt about it—steel was simply iron combined with such an amount of carbon as would enable it to be hardened by quenching. When Faraday spoke of alloying other elements with steel there could be no doubt what he meant. In later years, however, there arose a situation which is well described in Huntington and McMillan's *Text Book of Science—Metals* (1897), where it is said:—

> "The nomenclature of iron, already sufficiently unscientific, has been made more confusing by the introduction of a number of so-called steels, many of which are alloys of iron with other metals and contain but little carbon."

This situation still exists. If we had kept to the original interpretation of "steel," as iron which had been rendered capable of hardening by absorption of carbon, it would be impossible to call any material steel which did not contain enough carbon to produce hardening, and still less could we call any material steel which would not harden.

Actually the term steel is now applied not merely to combinations of iron with carbon capable of being hardened by quenching,

but also to such combinations in which the carbon present is insufficient in amount to confer this capability, such, for example, as the many millions of tons of mild steel employed annually for structural and other purposes which cannot be effectively hardened in this way. The description steel is also applied to alloys of iron with other elements, whether or not these alloys possess the property of hardening, and whether or not their special properties are due mainly to carbon.

Binary, Ternary, Etc., Alloys

Some explanation is necessary with regard to the use made by the author of the terms "binary" and "ternary" alloys. In the generally accepted nomenclature and classification these terms refer to alloys of iron with one or two elements respectively, carbon, if present, being reckoned as an alloying element.

The strict application of this classification in practical ferrous metallurgy is, however, somewhat difficult and liable to cause confusion where elements are present in what may be described as an extraneous way. Thus carbon is almost always present whether intentionally or not, and frequently such elements as silicon and manganese. It is difficult in such cases to decide the limit of percentage in these elements which may be considered as having sufficient influence on the properties to affect the classification of the particular steel concerned.

In another sense ordinary carbon steel, *e.g.*, such as used for castings, may contain manganese and silicon each between ½ and 1 per cent. Strictly this would be a quaternary steel, yet practical steelmakers would find this to be difficult of acceptance, that is, regarding it as an ordinary carbon steel. All things considered, the author has in the present instance felt himself justified in classifying steels containing one main alloying metal as "binary," and those containing two as "ternary," irrespective of the carbon content. He has further been led to this decision by the consideration that to Faraday steel was iron combined with carbon, and that his expressed intention was to investigate the influence of other elements alloyed with simple carbon steel or with iron. That is, either steel or iron was the base, and we may reasonably call, for example, his alloy of chromium with steel a "binary steel alloy"; his alloy of platinum and silver with steel a "ternary steel alloy." This course has been followed throughout the book.

Work Inspired by Faraday

As mentioned by Stodart and Faraday in their Royal Society paper of 1822, their work on steel and alloys aroused much interest

on the Continent, and several of their alloys were " diligently and successfully made " there, and " very good specimens of some of them " were handed to Stodart and Faraday. The author has not been able to trace further evidence concerning these particular specimens, but in his *Memoire sur la Fabrication et la Commerce des fer à Acier dans le Nord de l'Europe*, M. F. le Play states that researches based on the same idea as Stodart and Faraday's were undertaken " for several years in all parts of Europe." Work proceeded with special activity in France and, under the auspices of the Société d'Encouragement pour l'Industrie Nationale, " more than 300 experiments were made on alloys of iron with most other metals. Many alloys prepared on a small scale in this way were tested by the best steelmakers and judged to be of excellent quality. . . . However, all these researches, which continued until the year 1824, apparently led to no results on a manufacturing scale ; and since then," said le Play, writing in 1846, some twenty-two years later, " few attempts have been made to manufacture alloy steels." The reason for these fallow years after such an encouraging start was probably the same in France as in this country ; the initial experiments were a generation or more ahead of the needs of the times.

However, there is no doubt that the general interest and promising results of Faraday's work on steel alloys caused much attention to be given to the subject in France. Two important papers were published by J. B. Boussingault and M. P. Berthier respectively in 1821,* and the following passages from Berthier's paper are of special interest :—

" The idea of introducing chromium into cast steel suggested itself to me by the interesting work of M. Faraday with regard to alloys of different metals with steel.

" I found that such chromium steel possesses properties which render it useful for many purposes.

" I made two alloys of cast steel containing chromium, one with 1 per cent. and the other with 1½ per cent.

" M. Merimée has been kind enough to have these steels tested by an intelligent maker of cutlery.

" The materials forged satisfactorily, the first one being more easy to work than ordinary cast steel.

" A knife and a razor were made, also two blades. The remarkable damascene appearance was noteworthy, resembling steel alloyed with silver."

Berthier pointed out that it would be better to make such steel with a chromium-iron rather than cemented steel with chromium

* Upon the Combination of Silicon with Platinum and with Regard to the Presence of Steel. J. B. Boussingault, *Annales de Chimie*, XVI., 1821.

Alloys of Chromium with Iron and Steel. M. P. Berthier. *Annales de Chimie*, XVII., 1821.

ore. Singularly enough, he experimented with chromium ore from Philadelphia, U.S.A., where he said it was found in abundance.

In the *Bulletin de la Société d'Encouragement pour l'Industrie Nationale* for July, 1821, there appears an important reference: "Note sur les expériences faites par la Commission de la Société d'Encouragement pour l'amélioration de l'acier par son alliage avec diffèrentes substances." In this paper an account is given of the work of a committee "charged to repeat and continue the experiments commenced in England on the improvement of steel by alloying it with different substances." Stress was laid upon the complexity of the problem and the vast amount of labour involved. M. Bréant evidently took the leading part in the work, making numberless experiments and melting several lots of metal every day—sometimes eight to ten—in his laboratory. In many instances he even forged his own ingots. After many failures and disappointments he obtained "results which the most practised eye could not distinguish from certain Indian steels." Evidently wootz was adopted as a standard or ideal in France at that time no less than in England. The report also pays tribute to the work of M. Berthier, who greatly assisted the committee and who "had been engaged with these combinations for several years and, even before the publication of Faraday and Stodart's work, had alloyed titanium with steel, which the English chemists attempted without success."

The French investigators evidently paid much attention to the phenomenon of damascening, and they arrived at the conclusion that this could be produced in almost any steel by the exercise of patience and skill. In other words, the damask was not inherent to a particular steel and not necessarily an indication of a new alloy, though it was possible to recognise certain distinguishing characteristics in the damask of some alloys. From an analysis of certain fragments of old blades the French investigators concluded that they did not contain either gold, silver, platinum or palladium. They still thought it possible and even probable that some of these metals might be found in other Oriental blades because "it is a natural idea to harden steel as one hardens copper."

The indefatigable M. Bréant "continued his researches with an ardour which threatened his health," and in the course, apparently, of a few weeks he made "three hundred experiments on combinations of steel with platinum, osmium, gold, silver, copper, tin, zinc, lead, bismuth, manganese, uranium, arsenic, boron, etc." One wonders what further remarkable combinations were covered

by that naïve word "etc."! If there had been followers round Faraday of the calibre of the worthy M. Bréant, and if the problem of damask had not been allowed to become a central point of interest in the French investigations, the history of metallurgy in the nineteenth century might have been considerably changed.

One more point of interest remains to be extracted from the note cited: M. Merimée reported to the Council of the body mentioned that he had written to London in order to obtain a quantity of Indian steel sufficient for melting on a large scale, with a view to obtaining a better knowledge of its quality and nature. The India Company, learning that the steel was required by the Société d'Encouragement for experimental purposes, made a free gift of a quintal of the metal, asking only to be informed of the results of the experiments—truly a pleasing instance of international co-operation.

Nor was the influence abroad of Faraday's work at the Royal Institution by any means confined to France. In opening the discussion on the author's paper "The Development of Alloy Steels," presented to the Empire Mining and Metallurgical Congress, 1925, Colonel N. T. Belaiew, C.B., said that the work of Stodart and Faraday had a very wide repercussion in many countries outside their own. He added that if some of the contemporaneous metallurgical papers of that date in other countries, and more particularly in his own country, Russia, were consulted, it would be realised how important that work had been regarded. For example, the work of Stodart and Faraday in 1819–1824 aroused considerable interest in Russia and gave rise to a range of experiments which were made by General P. Anossoff, Engineer of Mines, Director of the Zlatoust Steel Works in the Ural District, who tried to explain the properties of carbon steels on the assumption that carbon steel was an alloy steel. He first set to work by repeating the experiments of Stodart and Faraday, and only by degrees did he come to the conclusion that carbon steels were not alloy steels, but that their properties were to be ascribed to carbon.

Further evidence might be given, but enough has been said to show that Stodart and Faraday's work aroused great and widespread interest at the time, and inspired others to conduct many laborious experiments which must have contributed to general metallurgical knowledge and progress, though they nowhere led to the immediate development of alloy steels on an industrial scale. After the year 1824 there was a long interval, during which little or nothing was done in the way of carrying on the systematic research which Faraday initiated. Much progress was required in the methods, materials and general knowledge of steel metallurgy before steel alloys could be made and used on a commercial basis.

Improvements in Steel Manufacture

In the light of subsequent knowledge it can now be seen that better methods of manufacturing ordinary carbon steel were essential before the world could advance to the development and use of alloy steels on a large scale. As regards the improvement of methods for the manufacture of carbon steel, the work of Bessemer and Siemens deserves special mention, besides that of many others mentioned in Chapter VI, and later in the present chapter.

Undoubtedly it was Heath who first discovered the full importance of the use of manganese in steelmaking, and it is not too much to say that this discovery led ultimately to revolutionary improvements in the art of steel manufacture. Heath patented the employment of metallic manganese, or, as he called it, "carburet of manganese," in 1839. A relatively small addition of manganese, only ½ to 1 per cent., removed the red-shortness of inferior coke-made irons and resulted in the production of sound cast steel. The importance of this invention was immediately appreciated in Sheffield. It was used extensively and proved of great benefit to the trade of the city. Unfortunately for himself, Heath was sufficiently confiding as to tell his licensees that they could save money by putting oxide of manganese and carbonaceous matter into the crucible with the blister steel, thus making his "carburet of manganese" (actually metallic manganese) on the spot instead of purchasing it ready made. This piece of information saved the licensees much money, and lost Heath his royalties, for the law decided that the use of oxide of manganese and carbonaceous matter was not Heath's patent. This does not alter the fact that great credit is due to Heath for his discovery and introduction of the use of manganese.

The discovery, by Bessemer, of a method for making low-carbon or mild steel was one of the most important advances ever effected in metallurgy. Its immediate effect was a great reduction in price and improvement in quality of steel, resulting in an enormous increase in the use of this material. The first public announcement of the process was made at the Cheltenham meeting of the British Association in 1856, and though it met with much scepticism and criticism, and no little active opposition, the process was soon being worked under licence in all the principal countries of the world. Certain prominent manufacturers in Sheffield rendered valuable aid to Bessemer during the earlier and critical period of development of his great invention. Briefly, the Bessemer process consists in the production of steel direct from the molten iron. Air blown through the molten cast iron in an "acid converter" burns out the carbon and silicon, and in the "basic converter"

also the phosphorus. The addition of spiegeleisen or ferro-manganese to the purified iron then produces steel of any desired carbon content, the manganese freeing the iron from oxygen and removing red-shortness, while the carbon converts the decarbonised iron to steel. Various improvements of the original process have since been effected, but the general principle of decarbonisation of cast iron, followed by controlled recarbonisation, remains as the basis of making satisfactory steel in large quantities and at low price. As such, the invention of the Bessemer process may be regarded as the opening of the Steel Age. Until ordinary carbon steels had come into general industrial use, it was hardly possible for special alloy steels to be thus employed.*

Importance of Carbon

The ability to make a full range of carbon steels was really the first stage in the modern development of steel. Carbon was, of course, used in all the early steels from the days of antiquity, but, until the invention of the Bessemer process, the employment of steel was on a comparatively small scale and confined chiefly to high-carbon steels required for hardness and to take a cutting edge.

Reference may here be made to the only systematic early research that the author has been able to trace, as to the strength of steel containing different proportions of carbon varying from 0·33 to 1·50 per cent. These researches were described in a paper by Mr. T. E. Vickers in 1869, in Kohn's *Iron and Steel Manufacture*. Seeing that little information was then available, this contribution was of an important character, as it dealt with the analysis and the mechanical strength—including elastic limit, breaking load, elongation, and drop test—of the steel under observation. Mr. Vickers also noticed that the specific gravity of steel decreased with an increasing percentage of carbon.

It is a curious metallurgical fact that no steel with any appreciable proportion of an alloying element has yet been found capable of taking quite the same hardness in a cutting edge as carbon steel at ordinary temperatures of use. The use of high-speed steels is, of course, exceptional, cutting tools of these materials being used at or near red heat. Toughness, however, is not a characteristic of these higher carbon tool steels. Improvements have therefore been made in oil-drilling bits and cutters, and also drill steels for quarrying and metallurgical mining, by the addition of small quantities of alloying elements, for example, manganese, nickel, chromium, vanadium and molybdenum, according to the

* It may be added that between 60 and 70 per cent. of the steel output of to-day is produced by the open hearth processes. This, however, is a subject outside the scope of the present book.

class of service for which the steel is to be used. These additions are often comparatively small in quantity—only about 0·20 per cent. of vanadium, or up to 0·60 per cent. of chromium. The expectation in such cases is that the improved toughness and cohesion conferred will compensate for such slightly lower hardness as is experienced and, on the whole, provide an edge which lasts better in service.

A certain percentage of carbon is essential in many alloy steels in order that the distinctive properties conferred by other elements may be fully developed. Yet it is seldom that the amount of carbon in steels exceeds 1·50 per cent.; in fact, the greater portion of steel in use does not contain one-fifth of this percentage, and it is remarkable that so small a proportion of this element should have such powerful effects.

It is true that in some cases carbon is not wanted, and alloy steels are being produced in which there is only about 0·03 per cent. of carbon present, but for the majority of the ordinary and cheaper steels carbon is relied upon to impart the desired qualities and characteristics. This must, of course, be the case when steel is required which will harden by sudden cooling in water, oil or air, and the carbon is then usually over about 0·60 per cent., in varying quantities according to the steel desired.

The Work of David and Robert F. Mushet

The work of the Mushets, father and son, the latter of whom in 1876 received from the Iron and Steel Institute the much-prized award of the Bessemer Gold Medal, will always be remembered in connection with the early development of alloy steels. The first air-hardening tool steel, evolved by Mushet and patented in the year 1868, contained about 2·3 per cent. of carbon, 2·57 per cent. of manganese, 1·15 per cent. each of silicon and chromium, and 6·62 per cent. of tungsten. Steel of this type made possible about 50 per cent. higher cutting speeds than could be used with ordinary high-carbon steel. It did not require hardening by quenching in water or any other liquid, but hardened by cooling in air, owing to the tungsten and manganese in its composition. The original material was rather in the nature of cast iron than steel. Its applications were limited, the alloy was relatively brittle and useful chiefly for tools, its manufacture being for a long time shrouded in mystery. Much aid was rendered in the development and improvement of this material by the firm of Messrs. Osborn, of Sheffield, steelmakers of long experience and repute. The Mushet tool steel represented an important practical advance, but, as shown by the metallurgical literature

of the 'seventies, there was at that date but little scientific knowledge of alloy steels in the modern sense.

Importance of Ferro-Alloys

In breadth of conception, Faraday's researches on steel and alloys were far beyond anything which had previously been attempted in this field, in fact, they were the first systematic investigation of a range of alloys as distinct from single alloys. Early investigators in this field were met by the difficulty that the materials they obtained for alloying purposes were produced, in most instances, in small quantities and at great expense; also, they were often impure or contained high carbon. Faraday was considerably more fortunate than his predecessors in this respect, for he was able to obtain relatively large quantities of a number of rare elements from Dr. Wollaston. He had not, however, the advantage of ferro-alloys of the ordinary metals, which offer the best means of introducing alloying elements into steel. These useful materials were not available until many years later, and even then at first in an imperfect form.

The credit for first appreciating the importance of ferro-alloys in the manufacture of steel appears to belong to M. P. Berthier, who, in a report on alloys of chromium with iron and steel,* stated that he had spent much care on the preparation of ferro-chromium, not solely because he believed such material had in itself special value, but because he believed it would be found useful as a means of introducing chromium into cast steel. In the face of this statement, it is surprising to find that this important point was at first overlooked by Baur and others until their investigations led them to the same conclusion. Incidentally, it may be noted that M. Berthier acknowledged frankly in the report mentioned that the idea of introducing chromium into steel was suggested to him by Faraday's first paper on the alloying of various elements with steel. This statement is important, because it has been stated that Faraday obtained his idea from Berthier's work. Also, as Faraday inspired Berthier, who was the first to appreciate the importance of ferro-alloys, it may be claimed that Faraday's research on alloys of steel was useful in yet another direction—it led to the first appreciation of the value of ferro-alloys, which are now regarded as indispensable to the commercial production of alloy steels.

The Work of the Terre Noire Company

Notwithstanding the contributions made by isolated workers, matters progressed but slowly in the field of alloy steels for many years after the pioneering efforts of Faraday and those whom he inspired in various countries. Indeed, no great advance appears

* *Annales de Chimie*, 1821, Vol. XVII.

to have been effected until that indefatigable band of workers arose in the St. Etienne district of France. These comprised Messrs. Jordan, Jullien, Euverte, Pourcel and Gautier, who then formed the working organisation of the Terre Noire Steel Co., originally founded in 1819.

These gifted Frenchmen set out boldly along the road trodden so laboriously by Faraday many years before, endeavouring to find by a series of interesting researches the influence of various metals when alloyed with iron, including the effect of carbon, silicon, manganese and phosphorus. The attempt was made under circumstances much more favourable than those with which Faraday had to contend. The French investigators were a group of experienced metallurgists conducting their researches in a steel-works with all the facilities of that later date ready to hand. Apart from the general advance in metallurgical knowledge, equipment and practice, they had also the benefit of the rapidly growing industry for producing ferro-alloys, specially ferro-manganese, the manufacture of which was so ably developed by M. Pourcel, and for which there was an extensive use in the production of mild steel.* This was fully recognised by the Iron and Steel Institute, who in 1909 awarded him the distinguished honour of the Bessemer Gold Medal.

Their products were at first necessarily somewhat imperfect, as the ferro-alloys obtainable, though superior to anything before known, were too highly carbonised, or were not sufficiently rich in their respective special elements.

The same workers followed up their researches, and the results were shown in the wonderful exhibition of Terre Noire products at the Paris Exhibition of 1878. It was a display which the author, then only nineteen years of age, will never forget, as it had the strongest possible influence upon his mind, so much so that he translated for his own use the whole of their extensive brochure of some sixty pages, including the results of several hundred tests.

The Era of Special Steels

It is the principal aim of this book to impart new information concerning Faraday's investigations on alloys of steel, and to show that he was indeed the pioneer of systematic research in this important field, but it is only right to emphasise the long and

* No one has more freely recognised than M. Pourcel the efforts of Mr. Prieger of Bonn and Mr. W. Henderson of Glasgow. The Henderson process was for several years carried out at the Terre Noire Works. The work of M. Pourcel eventually, however, proceeded on quite different lines and with the blast furnace. This resulted in the price of ferro-manganese (now absolutely necessary for the production of nearly all modern steel), which by the crucible process cost no less than £80 to £100 per ton, or by the Henderson process about £56 per ton, being at once reduced to £16 per ton—a truly remarkable metallurgical achievement. This figure was later reduced to the very low selling price of £8 per ton and is now about £11 per ton.

painful sequence of discoveries which led to and were essentially preliminary to the remarkable metallurgical developments of the past half-century or so.

Though chemists of other countries discovered many important metallic elements, as referred to on p. 69, British workers were by no means idle. Indeed, the work of Robert Boyle, Benjamin Huntsman, Abraham Darby, Joseph Priestley, Henry Cort, John Dalton, Humphry Davy, Michael Faraday, Robert Heath, David and Robert Mushet, Henry Bessemer, William Siemens, Lowthian Bell, George Snelus, Sidney Thomas, Percy Gilchrist, and others—to say nothing of those belonging to a period nearer to our own times—contributed greatly to the state of chemical and metallurgical knowledge at the middle of last century. Nevertheless, despite the labours, amongst scores of others, of such pioneers as Agricola (Germany), Dud Dudley (England), Pettus (England), Réaumur (France), Swedenborg (Sweden), Huntsman (England), Rinman (Sweden), Cronstedt (Sweden), Bergman (Sweden), Scheele (Sweden), De Elhuyar (Spain), Vauquelin (France), Vandermonde (France), Berthollet (France), Heath (England), Mushet (England), Berzelius (Sweden), Berthier (France), Percy (England), and Faraday himself, it was not until about the decades 1860 to 1890 that there occurred the great advances and tremendous burst of activity in metallurgical science of which we see the striking results and benefits to-day.

With the exceptions already noted, the field of alloy steels lay fallow for many years after Faraday left it. It was the discovery and invention of manganese steel in 1882 which showed that the new world already indicated by Faraday was there ready to be explored. This exploration has taken place rapidly during the last thirty years, including the discovery and invention of silicon steel, nickel steel, chromium steel, tungsten steel, high-speed tool steel, non-corroding, heat-resisting and many other types of special steels.

It has been said by many independent authorities that the author's work in alloy steels, particularly in the discovery and invention of manganese steel, represented the beginning of a new era, but in the light of all the evidence collected during the present investigation of Faraday's work in this field the author freely acknowledges himself to be but a follower of that great master. It is true that when he made his first discoveries in the field of steel alloys the author did not know of Faraday's work in this direction. His work was thus independent in conception and execution, but it was based on the same main thoughts and proceeded along the same general lines of enquiry as Faraday's pioneer work of some sixty years before. The enormous practical importance of the

results which emerged from the discovery and invention of what is now universally termed the Hadfield manganese steel was due in large measure to the improved facilities available, as compared with those of Faraday's time, including a wider general knowledge of metallurgy, better supplies of materials, perfected appliances and other advantages. Curiously enough, manganese—the alloying element in the material which opened the era of "special steels" in the modern sense of the term—is only to be found in traces in any of Faraday's specimens, and was certainly not added deliberately. Nevertheless, the author maintains that to Faraday belongs the credit of being the pioneer of research on alloy steels.

Manganese Steel

At the time when the author commenced his metallurgical work in the 'eighties of last century the amount of definite scientific knowledge available concerning alloys of steel was very small indeed. In fact, it was almost non-existent. Faraday had made a number of remarkable alloys, but none of them had been subjected to scientific investigation.

As already mentioned, it was largely the brochure issued by the Terre Noire Company at the great Paris Exhibition of 1878 that inspired the author to undertake a series of experiments on alloys of steel; and this, in turn, led to his discovery and invention in 1882 of manganese steel, concerning which Osmond, one of the leading scientific metallurgists of his time, said that "the discovery and invention of manganese steel was not only the discovery of a new alloy, curious, of great scientific value and yet useful, but in the history of the metallurgy of iron it ranked as a discovery equal in importance to that of the effect of quenching carbon steel, and was the only one of the same order which it had been reserved for our age to make."

The alloy now generally described as the Hadfield manganese steel, consisting of an alloy of iron with from 11 to 14 per cent. of manganese and about 1·25 per cent. carbon, is still one of the most remarkable materials yet produced. Its principal characteristics may be summarised as follows :—

(*a*) It is practically non-magnetic, notwithstanding the fact that it contains about 86 per cent. of iron.

(*b*) The alloy is greatly toughened by quenching instead of being hardened and made comparatively brittle, as is the case with carbon steel.

(*c*) It has high tensile strength (60 to 70 tons per square inch when suitably heat-treated), combined with extraordinary elonga-

tion, viz., 50 or even 70 per cent., exceeding that obtainable with the purest iron.

(*d*) Its resistance to wear by abrasion is greater the more severe the service to which it is applied.

The author's more recent researches* show clearly that while the non-magnetic properties of the Hadfield manganese steel, containing about 11 to 14 per cent. manganese, have their basis in the association of iron and manganese, the special and valuable characteristics upon which its many engineering uses turn are vitally dependent on the fact that it also contains carbon to the amount of 1 to 1½ per cent. Both quenching and annealing produce in manganese steel effects quite opposite to those obtained in most other steels. Quenching makes this non-magnetic steel tough and ductile, whilst annealing it for some forty hours at about 600° C. makes the steel hard, brittle and magnetic. When water-quenched and toughened, the forged material has a tensile strength of from 60 to 70 tons per square inch, combined with such ductility that the elongation is from 50 to 70 per cent. on 8 inches. The local constriction at the point of fracture is less than ordinary steel, the contraction of the sectional area being distributed nearly uniformly throughout the parallel portion of the test-piece. Even slight deformation of an article made of this steel is accompanied by a considerable increase in hardness of the material, and the highest wear-resisting qualities are developed under the hardest working conditions. In the undeformed state it is relatively soft, the hardness being then about 200 as measured by the Brinell test; the material gains greatly in hardness under mechanical deformation, the Brinell hardness number rising to 500 or even 580.

As already noted, water-quenched manganese steel is practically non-magnetic, and for this reason it has been employed in armoured and other structures near the magnetic compass in ships and aeroplanes.

Its electrical resistance is 71 microhms per cm.-cube, or seven times that of pure iron; the average thermal conductivity between 0° and 100° C. is 0·027 c.g.s. units, or about one-sixth that of pure iron; and the mean coefficient of expansion between 0° and 100° C. is 0·000018 per 1° C., or about 1½ times that of pure iron. These properties are the more remarkable when it is remembered that manganese steel contains about 85 to 87 per cent. of iron.

This steel has excellent casting qualities as regards fluidity and ability to fill moulds of intricate shape. Its fluid contraction is rather greater than that of ordinary steels, and amounts to from

* See "Alloys of Iron and Manganese Low in Carbon," *Jour. Iron and Steel Inst.*, 1927.

0·30 to 0·33 inch per foot, and the castings made from it are particularly free from blowholes. An example of the excellent results which can be obtained is to be seen in Plate LIV., representing a medallion of Faraday cast in the Hadfield manganese steel.

The reader desiring further information in regard to this steel should see the author's book, *Metallurgy and its Influence on Modern Progress*, and his various papers on the subject during the past fifty years.* Suffice it to say that the extraordinary combination of toughness and great strength obtainable in manganese steel by proper heat treatment and working renders it invaluable for such applications as special railway and tramway trackwork, the jaws and other wearing parts of crushing machines, the wearing parts of excavators and dredgers, wheels of mine cars, of which hundreds of thousands are at work, wire line sheaves for oil-well machinery, sprockets, clutches and hundreds of other articles exposed to severe conditions, in fact, wherever special resistance to shock and abrasion is required. During the Great War tens of thousands of British and Allied troops owed their lives to the protective helmets made of manganese steel.

Whilst the composition of this steel is the same as that first produced by the author, the manufacture of the material has been greatly improved, including the heat treatment, to which its most useful qualities are largely due.

An interesting example of the use of manganese steel is afforded by jaw-type crushers, produced by the author's firm. Some of these represent the largest yet made in Great Britain, and are intended for work in the construction of the huge Cauvery Metur Dam in India, which has a volume of nearly 2 million cubic yards. Each machine weighs about 100 tons and crushes 200 tons of stone per hour. These crushers are built entirely of cast steel, all the wearing parts being of manganese steel. They have a feed opening measuring 54 by 42 inches, and are capable of dealing with blocks of stone weighing over 2 tons each, reducing them to 6-inch cubes in about one minute. Without the use of manganese steel such a result would not be economically possible.

For layouts including points and crossings of railways, also street tramways and junction layouts, cast, forged and rolled manganese steel continue to be of the greatest value, and although claims have been made for the merits of heat-treated nickel-chromium steel castings for such purposes, these have not been able

* A full list of these, also other papers and addresses by the author, amounting to some 190 publications, mostly dealing with alloy and other special steels, is given in his published pamphlet entitled "Classified List of Papers from 1888 to 1930."

One-fifth actual size.

Medallion Portrait of Faraday modelled by F. J. Halnon, R.B.S., and cast from Manganese Steel.

[*To face p.* 266.

seriously to challenge the superiority of manganese steel. Much greater advantage might usefully be taken by the permanent-way engineers of our railroads of the facilities which now exist for the production of manganese steel rails and the economies in upkeep of the track which their use brings about. Experience in traction service all over the world proves that the cost of maintenance of ordinary steel points, cross-overs, and other special trackwork where wear is excessive, is from 6 to 12 or even more times that made of manganese steel.

As might be expected from its characteristic properties, manganese steel is difficult to roll or forge in any but plain, simple forms. Nevertheless, long experience gained in the manipulation and control of the material and its heat-treatment has made it possible to produce successfully rails, sheets, plates, and complicated assemblies of this steel.

The reversing 28-inch blooming and finishing mill at Messrs. Hadfield's works is believed to be the first erected having for one of its main objects the production of manganese steel rails. This mill is capable of reducing 15-inch square steel ingots, 5 feet long and weighing 25 cwt., to $2\frac{1}{2}$-inch square billets in a single heat. The normal output of such a special steel mill, that is, when engaged on ordinary steel, is about 1,200 tons per week, but on hard and difficult alloy steels this total is greatly reduced, for such steel cannot be rushed through in the same manner as mild carbon steel. Moreover, all the appliances and treatments necessary involve time and reduce the output. Ingots of manganese steel are rolled into rails, up to the heaviest section in demand and up to 55 feet in length. The hydraulic shears used in conjunction with the mill are capable of shearing the "Era" manganese-steel blooms, when hot, up to 10 inches square. The total weight of the mill is about 1,600 tons, including the driving motor, which is rated at 3,200 h.p., and is capable of developing 11,600 h.p. for short periods.

For many years manganese steel was regarded as practically unmachinable, and its use was therefore restricted to parts which could be cast, rolled or ground into shape. Recently, however, tool steels have been developed—themselves wonderful examples of the advance in knowledge of alloy steels—which are quite capable of machining manganese steel. Some of these alloys contain no fewer than eight elements besides iron, namely, carbon, manganese, chromium, nickel, tungsten, cobalt, vanadium and molybdenum. The combined effect of these various elements is to enable the harder form of the carbon present in the way of carbides of iron to retain its hardness to an almost incredible

degree, even under the specially severe conditions of heating and mechanical stress encountered when cutting manganese steel.

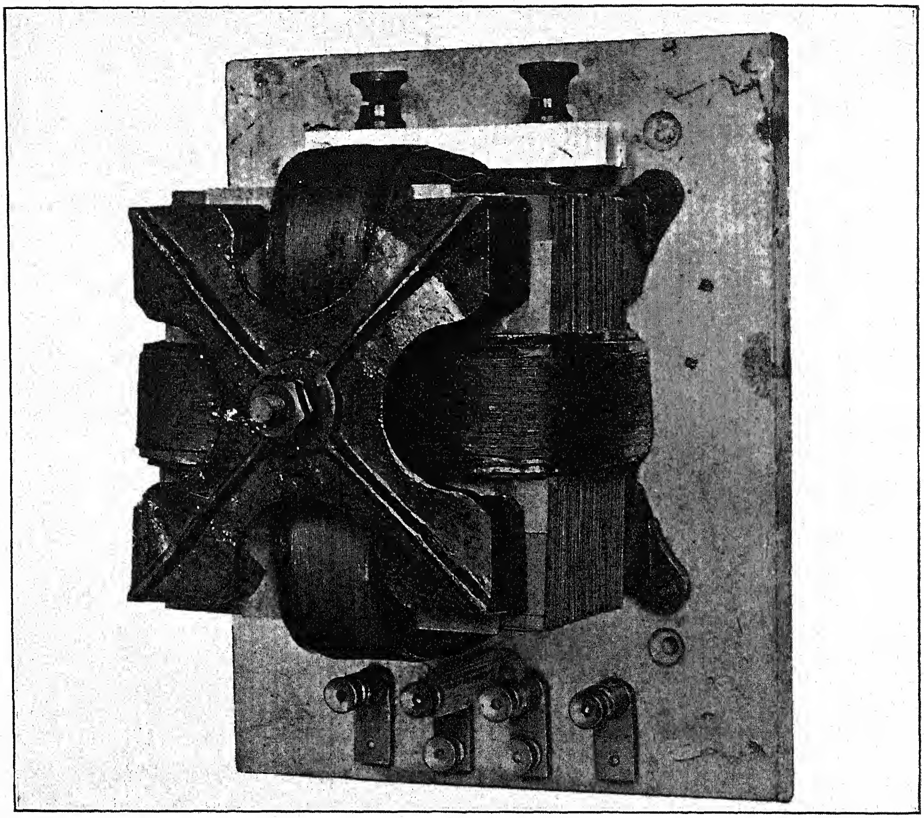
Whilst manganese steel must necessarily remain more difficult to machine than ordinary steel, with sufficiently powerful tools available, it is now practicable to carry on machining operations in a much more rapid and economical manner than by the usual expedient of grinding. Thus in the machine shops of the author's firm, working on a spindle of water-toughened manganese steel 3 inches in diameter, and using a turning tool 1 inch square and with $\frac{1}{32}$ inch feed and $\frac{3}{16}$ inch depth of cut, at a cutting speed of 11·8 feet per minute, the tool traversed a distance of 20 inches before requiring regrinding. Tests made with a drill $1\frac{1}{4}$ inches diameter on the webs, $\frac{5}{8}$ inch in thickness, of rolled manganese steel rails showed that many holes could be drilled through the web at 50 r.p.m. before regrinding of the drill was necessary, the average time for drilling each hole being six minutes. Even better practice is obtained with the latest tool steels.

For many purposes the non-machinability of manganese steel has hitherto prevented its use, because it could not be readily provided in the precise forms necessary. It seems probable that reconsideration of its merits in the light of this new fact will still further extend the already varied applications of the material.

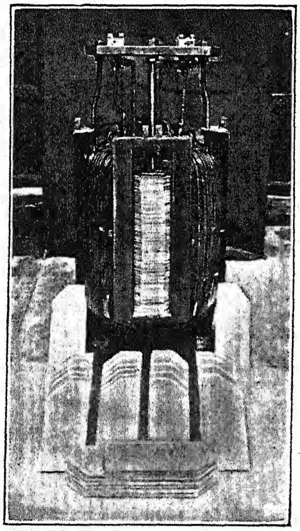
Silicon Steel

The author's attention was specially directed to the effects of silicon on iron as long ago as the year 1882. Thereafter, as the outcome of many years of research, the invention and application of silicon steel were developed and perfected. Numerous difficulties were experienced in the early stages of the introduction of this steel made under the author's patents. The history of these developments and how they were overcome is given in his book, *Metallurgy and Its Influence on Modern Progress*, where reference is also made to the series of researches, these being chiefly of a physical nature, which he carried out with the late Sir William Barrett, F.R.S., and Professor W. Brown on manganese, silicon, aluminium, chromium, nickel, tungsten and other alloy steels. Many peculiar and valuable physical properties of these alloys will be found described in the joint papers published by them in the Proceedings of various scientific and technical societies.

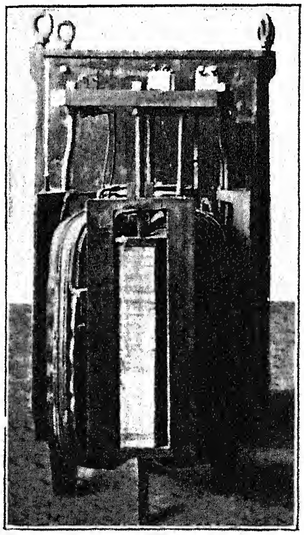
Steel containing about 3 to 5 per cent. of silicon has higher permeability at low forces, lower hysteresis loss, higher resistance, and under magnetisation by alternating currents has lower eddy-current loss than pure iron. The lower eddy-current loss is due to its higher electrical resistance, namely, from 10 to 12 microhms per cm. cube higher than that of pure iron for each 1 per cent.



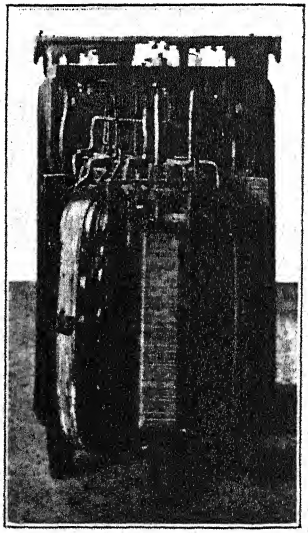
THIS ILLUSTRATION REPRESENTS THE ORIGINAL FIRST TRANSFORMER CONSTRUCTED IN 1903 OF SILICON STEEL MADE AND PATENTED BY HADFIELD, AND IS NOW IN THE PERMANENT POSSESSION OF THE SCIENCE MUSEUM.



40 K.W. SILICON STEEL TRANSFORMER, CONSTRUCTED IN 1905.



60 K.W. SILICON STEEL TRANSFORMER, CONSTRUCTED IN 1906.



40 K.W. TRANSFORMER, OF BEST TRANSFORMER IRON, CONSTRUCTED IN 1905.

To face p. 269.]

of silicon in the alloy. The maximum permeability of rolled sheets of silicon steel was found to be 25 per cent. higher than that of pure iron, whilst the hysteresis loss is initially about two-thirds that of pure iron and has been found even to decrease during a period of years in service. The property of improving during use instead of ageing is in marked contrast to the behaviour of charcoal iron and the early dynamo and transformer steels, for the hysteresis loss in these materials often increased by 100 per cent. or more after a few months, and necessitated the periodical dismantling and annealing of transformer plates. Owing to further improved practice in manufacture, this silicon steel can now be produced having a total loss only slightly exceeding 1 watt per kilogram when tested at 10,000 gauss maximum induction and 60 cycles per second, and a permeability of 8,000 can be reached.

The first transformer using silicon steel made and patented by the author was built in 1903. This was an experimental apparatus, weighing only 30 lb.; its characteristics proving excellent, transformers of 40 kw. and 60 kw. were at once built and put into use by the Sheffield Corporation Electricity Department, using silicon steel of similar composition. These transformers were placed in service in 1905 and 1906 respectively, and their magnetising losses when tested in 1921 were found to be appreciably lower than when first put to work. Owing to a fire at the sub-station, not due to any fault of the transformer or its core material, the 40-kw. transformer was damaged beyond repair in 1922 after seventeen years' service. The 60-kw. transformer was taken out of service in 1927, after being in use for twenty-one years.

The author's silicon steel was introduced commercially in this country by his licensees, Messrs. Sankey, and later by Messrs. Lysaght, under the name "Stalloy"; in the U.S.A. by his licensees, the American Sheet and Tin Plate Co., the General Electric Co. and the Westinghouse Co.; in Italy by the Magona Company and in other countries. To each of these much credit was due for their help in overcoming the unusual conditions met with in the introduction of this steel.

The total amount of electric energy now annually passing through transformers, including transformations both at the generating end and the consumer's end of the transmission line, in which silicon steel cores are used, is estimated to be something like 500,000 million kilowatt hours, and the use of the Hadfield silicon steel effects a saving in energy losses of at least 2½ to 3 per cent. This is equivalent to a monetary saving of about £26,000,000 annually, so it will be seen how important this invention has been to the world.

As an interesting contrast it may be mentioned that in one of the

latest and largest sets of transformers yet produced and built in the U.S.A., each unit, with a capacity of 40,000 kw., 35 feet in height, weighing no less than 300 tons, and requiring three large tank cars holding 32,000 gallons of oil to fill it, contains in its core no less than 63 tons of silicon steel. This equipment consists of seven transformers, thus altogether requiring about 450 tons of silicon steel. Compared with this giant set of transformers it may be mentioned that the core of the first transformer of the Hadfield silicon steel made experimentally and put to work in 1903 weighed only 6 lb.

This great development of silicon steel now used on such a large scale throughout the world is fully described in the author's book previously mentioned. Thanks are there expressed to those who helped him to bring about this advance, including not least his licensees in this country, the United States and other countries.

In the useful publications known as the *Research Narratives*, issued by the United Engineering Society of New York for its Engineering Foundation, representing some forty-four societies with more than 200,000 members, No. 91, Vol. 4, fully narrates the history of the Hadfield silicon steel, without which modern transformer construction would not be practicable. The small transformer referred to and made by the author in 1903 was the first practical application of this invention, and is now the property of the nation at the Science Museum, South Kensington.

Whilst great credit is due to the electrical engineers, chiefly in our own country and the United States, for their improvements in the design of transformers, nevertheless, without the invention of the Hadfield silicon steel they could not have obtained the remarkable results mentioned. The first of a series of interesting articles by the author and Mr. S. A. Main, B.Sc., on the various aspects of Faraday's work relating to electrical science and metallurgy recently appeared in *World Power* for September, 1931. The important question is there dealt with from the electrical engineering point of view, regarding the transformer from the days of Faraday's induction coil down to modern times.*

It may be interesting here to state that quite recently the author made an estimate of the advantage and gain generally to the world resulting from two of his inventions, that is, manganese steel and

* Attention is also drawn to that wonderful collection of transformer exhibits at the Science Museum, South Kensington, the assembling and arrangement of which afford great credit to the director and those who have assisted. They are indeed a national asset and a tribute to the discoveries, inventions and research of the British electrical engineer. The exhibits are well and fully described in the official catalogue, "Electrical Engineering," compiled by Mr. F. St. A. Hartley. This includes the sections dealing with the history, generation, motors, transformation, measurement, transmission and distribution, switch gears and protective devices, and will be found of great service to those interested.

silicon steel. Whilst it is not easy to assess the full value of the metallurgical progress which these materials represent in themselves and have brought about in their applications, yet upon collecting the various data available it has not been found possible to obtain such an estimate.

The author asked an independent authority to check and further elaborate certain figures of totals, and to his surprise found that his own calculations had under-estimated these total values of world advantages and savings, and that it could be stated that the savings already resulting from these two inventions—manganese steel, by its extraordinary combination of the qualities of extreme hardness and great toughness, and silicon steel, by its very considerable reduction of energy losses in electrical machinery—now amount to the immense total of between £650,000,000 and £700,000,000. This is a striking proof of the advantages brought about by the introduction and use of alloy steels, of which undoubtedly Faraday may be correctly described as being the pioneer.

The many difficulties which were encountered in the manufacture, introduction and application of these two alloy steels can be imagined, but after much perseverance they were gradually overcome by the author in the research laboratories and works of his Company, and later assisted by his various licensees.

There appear to be no other products in sight able to take the place of manganese steel and silicon steel, so that unless new concepts of engineering practice emerge, and this does not appear to be likely, the immense monetary and other savings mentioned in the foregoing paragraphs will continue, in fact, no doubt on an increasing scale, with consequent great benefit to mankind.

As most inventions form the subject of patents it may be permissible to make the following reference. Sometimes patentees are accused of creating monopolies under patents granted to them for their inventions, but this, in fact, is not really the case, as the public is not thereby prevented from doing anything they were lawfully entitled to do previous to the grant of a patent, but only from using the new invention during the life of the patent. In face of figures such as those above mentioned, in which the patentee obtained only an infinitesimal portion of the value of his inventions, it is clear that the public does ultimately derive great benefit from a wise system of patent laws and practice under which patents for valuable inventions are granted for a limited period.

Presentation to the Science Museum

Exhibits representing the author's discovery and invention of manganese steel and his early experimental work on this material, also his discovery and invention of silicon steel, including the original specimens of these alloys and the first transformers built

with Hadfield silicon-steel cores, have been presented by the author and accepted by the authorities of the Science Museum, South Kensington. These important records of British progress and invention have thus found a permanent home along with Stephenson's *Rocket;* Boulton's, Watt's and Trevithick's engines; Parson's original steam turbine; and many other historic exhibits.

Following his work on manganese and silicon steels, the author has also carried out correlated studies, on alloys of iron with aluminium, chromium, nickel, tungsten, cobalt, molybdenum, copper, titanium, and other elements. In almost every case these researches have covered and described methods of manufacture; chemical composition and analysis; properties of the metal as cast, and as rolled, forged, hammered, or pressed; heat treatment; mechanical qualities, including elasticity, tenacity, elongation, and resistance to shock; hardness tests; microstructure; electrical and magnetic qualities; thermal conductivity; resistance to corrosion and erosion; and other properties where possible. In many instances specimens of the alloys as they appeared were placed at the disposal of the scientists and specialists of many countries and in various branches of scientific work, the results being of great mutual benefit. As regards papers and other communications by the author, these now amount to 195, many of them relating to alloy steels and their characteristics.

Importance of Alloy Steels

The enormous advances in engineering and industry in general during the past thirty years or so have been due in large measure to the introduction of alloy steels, such as Faraday had in mind. At the time of his work on "steel and alloys" the world was in the Iron Age, which merged into the Steel Age when later Bessemer and Siemens-Martin discovered their processes for manufacturing steel. This in turn developed into the Era of Special Steels, commencing effectively with the author's invention and discovery of manganese steel.

Without iron we should inevitably revert to the conditions of the dark ages; and without alloy steels we should, in many respects, be cast back to the conditions of a century ago. Iron and the simpler forms of steel will not give us, for example, the hard-wearing toughness of manganese steel; the greatly reduced rusting qualities of chromium and other steels; the wonderful energy-saving properties of silicon steel as used for electric generators, motors and transformers; the special magnetic properties of tungsten and cobalt steels for permanent magnets, of manganese steel for applications where non-magnetic material is required, and of certain nickel-iron alloys where extraordinarily

high permeability at low inductions is required. In addition, there are non-scaling steels, steels which are strong and tough at low temperatures, steels possessing considerable strength at high temperatures, and many others.

In the course of an address to the graduates of the Institution of Mechanical Engineers in 1922, Sir Henry Fowler, K.B.E., said, in reference to early metallurgical work regarding alloy steels, that the author had brought out two steels which had done much to change certain practice with which mechanical engineering is associated—that is, manganese steel and silicon steel. He further remarked that this early work had been followed up enthusiastically by other metallurgists, and that "it was in no sense an exaggeration to say that the motor car and the aeroplane as we have them to-day are the result of this work of Hadfield's." The author would be the last to belittle in any way the great work accomplished in the same direction by engineers, designers and non-ferrous metallurgists, but, while special steels have not alone made the motor car and aeroplane possible, they are undoubtedly essential to each.

If the only ferrous materials at our disposal were cast iron, wrought iron and carbon steel—the materials, in fact, which were to be had when George and Robert Stephenson built the famous *Rocket*—the light, speedy and powerful motor car of to-day would be a physical impossibility. For the high speeds, stresses and temperatures involved in various vital parts of the modern car, wrought iron has insufficient tenacity and too low an elastic limit; plain carbon steel of the higher qualities, high in carbon, is too brittle; and ordinary cast iron is out of the question. If a motor car was built to a modern design, but with the materials used in Stephenson's *Rocket*, or even those available at the time of the production of the first automobile in this country, it would certainly break down after a few miles' running if, indeed, it would run at all. On the other hand, if the car were made mechanically strong enough with materials of the early type, it would be prohibitively heavy and costly to run. It is literally true, therefore, that, notwithstanding the advances in the science of engineering design, the motor car as we know it to-day would be impossible without special or alloy steels. The same may be said, in this sense, of the aeroplane and, in fact, of many of the triumphs of modern engineering constructions.

The author can claim to have been a true prophet in regard to the ever-increasing importance of alloy steels, for in his paper on "Alloys of Iron and Chromium," read before the Iron and Steel Institute in 1892, he used the following words: "The author

cannot but think that the special question of steel alloys or combinations will be eventually found to possess considerable practical importance to the world at large, and perhaps be the means eventually of enabling our civil and mechanical engineers to design and carry out works of a magnitude which, notwithstanding the great strides made during the last few years, even at present are not possible."

The truth of this forecast, made some forty years ago, has since been demonstrated in the most convincing manner. The wonders of modern engineering depend, more closely perhaps than is generally realised, upon the special qualities of the materials employed. Engineering science has progressed successfully just so far as the properties of the constructional materials available would permit. Improvements in materials have been followed immediately by advances in engineering practice. This was, in fact, for a time one of the main difficulties in the way of the extended use of high-pressure, high-temperature steam turbines, but recent advances in the direction of heat and corrosion resisting steels capable of withstanding high stresses at high temperatures have led to corresponding developments in application and practice.

From the practical standpoint the importance of alloy steels lies in the fact that they yield a greater range of mechanical properties than can be obtained in simple carbon steels, whilst they also yield either new physical properties or new combinations of properties. Whereas commercially pure iron (99·9 per cent. iron) has a tensile strength of 18 to 20 tons per square inch, and a ductility corresponding to 30 to 40 per cent. extension in the test-piece, high-tenacity alloy steels are now available which in the bar or mass form have tensile strengths exceeding 100 tons, or even more than 200 tons when in the form of wire. One of the nickel-manganese alloy steels prepared by the author showed a tenacity of nearly 60 tons per square inch, with an extension of 76 per cent. on an 8-inch test-piece; also manganese steel with its tenacity of 73 tons per square inch is often accompanied by no less than 73 per cent. of elongation. There is no other material extant which possesses the qualities of both high tenacity and elongation to the same degree.

According to requirements, it is possible, by the use of alloy steels, to reduce the weight of parts whilst retaining or increasing their strength; to obtain strength combined with special ductility, hardness, or resistance to fatigue; and, in fact, to obtain or accentuate almost any desired physical property. Alloy steels providing greater strength for given weight, or equal strength with

a saving of weight, contribute in an essential manner to large power units, high-speed machinery, and many other remarkable developments of recent times.

It would be difficult to mention all those whose labours have helped to bring alloy steels to their present position of high importance, but the author, who can look back a long way, believes that the following list represents most of those chiefly concerned: as regards Great Britain, Aitchison, Arnold, Brearley, Carpenter, Desch, Dickenson, Gowland, Harbord, Hatfield, Heycock, Mushet, Riley, Rosenhain, Saniter, Stead, Turner, Vickers; in the United States, Burgess, Campbell, Hibbard, Howe, Zay Jeffries, Matthews, Metcalfe, Sauveur, Stoughton, Strauss, White; in France, Brustlein, Charpy, Dumas, Frémont, Girod, Guillet, H. le Chatelier, Heroult, Moissan, Osmond, Portevin, Pourcel, Schneider; in Germany, Ehrensberger, Ledebur, Mars, Martens, Maurer, Monnartz, Straus, Wedding; in Sweden, Akerman, Benedicks, Brinell and Westgren; in Italy, Giolitti; in Japan, Honda; in Russia, Tschernoff and Belaiew.

In the pages which follow, a brief account is given of the applications of alloy steels in various classes of service, for example, services demanding resistance to heat and corrosion, high-speed machining, armament and ordnance, special structural purposes, and so on. Before proceeding to this, however, it may be interesting to give certain particulars concerning the scale on which alloy steels are now manufactured, as well as an indication of the vast sums of money which have been saved and continue to be saved by their use.

Output of Iron, Steel and Alloy Steels

The results of a careful estimate of the probable production of various classes of iron and of ordinary carbon steel during the early years of last century are given on p. 63. The production of alloy steels in those days was negligible as regards tonnage.

During the second half of the nineteenth century, however, the advance in the production of iron and steel was no less remarkable than the increase in quality and number of types. In 1845, for instance, the total production of iron and steel was about 2,512,500 tons, almost entirely by Great Britain, Germany, France and Sweden. In 1929, however, according to the Statistical Report of the American Iron and Steel Institute, the world's iron ore production was 186,000,000 tons; the production of steel ingots and castings was 119,000,000 tons; and that of pig iron and a small proportion of ferro-alloys amounted in all to 93,000,000 tons.

The world's output of pig iron was under one million tons per annum in 1800; at the time Faraday made his experiments on steel and its alloys, that is, 1818 to 1824, it had reached about two million tons; in 1850 about five million tons; in 1900 40 million tons; and in 1928, the peak year, about 98 million tons.

TABLE XXVI

American Output of Open Hearth and Electric Alloy Steel in 1928.
(*In order of total magnitude*)

Type of Steel.	Ingots.	Gross Tons. Castings.	Total.
Copper	868,500	10,700	879,200
Chromium	302,200	9,500	311,700
Medium manganese (1 to 2 per cent. min.)	231,200	30,400	261,600
Chromium-nickel	235,900	25,700	261,600
Chromium-vanadium	160,400	200	160,600
Nickel	125,400	2,200	127,600
Nickel-molybdenum	109,000	500	109,500
Chromium-molybdenum	61,000	7,100	68,100
Copper-molybdenum	67,200	—	67,200
Hadfield's manganese	7,100	51,500	58,600
Nickel-chromium-molybdenum	16,700	1,700	18,400
Vanadium	16,000	400	16,400
Molybdenum-manganese	2,200	1,400	3,600
Molybdenum	1,100	200	1,300
Others	206,700	19,300	226,000
Unclassified	570,000	2,300	572,300
Total	2,983,000	163,000	3,146,000
Open-hearth	2,629,000	84,000	2,713,000
Electric	354,000	79,000	433,000
Total	2,983,000	163,000	3,146,000

The world production of steel was still under one million tons per annum as recently as 1860, but by 1889 it had passed the 10 million tons mark, and in 1929 the enormous figure of 119 million tons was reached.

There appears to be a far advancing wave of production as new uses for this valuable material are constantly being found. The use of the metal iron to-day is about fifty times that produced in the early part of Faraday's career.

To-day one new big building being erected in New York calls for 125,000 tons of steel, and so the increased employment goes on with hundreds of new applications yearly, and these are now being intensified by the many new applications of non-corroding and heat-resisting steels.

An exceedingly interesting article in the *Iron Age*, December 26th, 1929, entitled "Types of American Alloy Steels," by Mr. E. F. Cone, gave output data which are reproduced in Table XXVI. From other sources it appears that the total output was actually nearer four million tons in 1928. Allowing, say, $1\frac{1}{2}$ million tons for the rest of the world, this would make a grand total of about $5\frac{1}{2}$ million tons per annum.

Savings Resulting from the Use of Alloy Steels

Two classes of savings have to be considered, those of material and those of direct monetary expenditure. In other words, conservation of supplies must be borne in mind as well as financial economy. According to Professor J. W. Gregory, F.R.S., the supply of iron ores would probably be exhausted within 130 to 150 years if the world's consumption of iron and steel went on increasing at the same rate as before the war. Alloy steels are of enormous importance in relation to the conservation of iron. The more general use of non-corroding steels, for example, would help greatly to reduce the wastage of iron by rusting. Apart from the question of the direct monetary loss involved by the wastage of metal due to corrosion, there is the further loss arising from interruption of work or service while the corroded parts are being renewed. There is also the possibility of serious accident from failure or breakage of corroded metal.

Again, to take only a single example, 1 ton of manganese steel will do the work of about 10 tons of ordinary iron or steel, owing to its remarkable durability in heavy service.

In the United States alone, the production of alloy steel ingots and castings rose from 181,980 tons in 1909 to 1,787,852 tons in 1918, and 3,146,000 tons in 1928, from which it is evident that the tonnage of special steels is quite sufficient to affect appreciably the conservation of iron.

The advantages derived from the use of alloy steels fall under two headings :—

(*a*) Certain alloy steels enable results to be obtained in engineering, chemical and other fields which either (1) could not formerly be accomplished, or (2) could only be accomplished with difficulty and extra weight of material.

(*b*) Certain alloy steels take the place of ordinary steel and effect great savings, *e.g.*, manganese steel, by its durability and toughness; silicon steel, by its enormous savings in energy losses; non-corroding steels, by avoiding corrosion; and so on.

It is impossible to assess the full value of the metallurgical progress which modern alloy steels represent in themselves and have brought about in their applications, not only by saving material and energy, but also by enabling results to be obtained which could not otherwise be secured. From a careful estimate it can be safely stated that as regards only two of the author's inventions, manganese steel and silicon steel, these have already effected savings amounting to very large sums. As more fully mentioned on p. 271, there appear to be no other materials in sight able to take the place of these two steels, so the immense savings mentioned are more than likely to continue, with increasing benefit to mankind.

Corrosion-Resisting Steels

Introduction.—As in the case of the heat-resisting, non-scaling steels mentioned later, no single alloy steel is applicable to all services in which resistance to corrosion is required. Corrosion as met with in industry or daily life occurs in many forms and from many causes. Co-operation between metallurgist, engineer and chemist is required to obtain the best results, and though laboratory or accelerated tests have been of undoubted value in the researches leading up to the introduction of special non-corrodible steels, they are often valueless or even misleading as a guide to the selection of the most suitable materials for specific practical cases.

Several years ago the author prepared a careful estimate of the annual loss in the world through corrosion. His figures, which were very carefully compiled from extensive data, showed this loss to be more than £500,000,000 per annum. The subject was fully dealt with by him in a paper entitled "The Corrosion of Ferrous Metals," read and discussed in 1922 before the Institution of Civil Engineers. This paper described the specimens prepared for the special committee of that body, including the ordinary and special steels, representing 1,330 separate bars allocated by the committee for the sea and atmospheric corrosion tests, as well as the laboratory and other mechanical tests carried out by the author. It may be mentioned that results have already been obtained from some of these specimens, many of which are, however, still under sea and atmospheric corrosion tests in different parts of the Empire, including Southampton, Plymouth, Halifax, Auckland, Colombo and the Port of Madras. These tests and examination of the

results obtained form the work of the special committee known as the Committee on the Deterioration of Structures Exposed to Sea-Action, appointed by the Institution of Civil Engineers.* This committee, in the founding and work of which the late Sir John Wolfe-Barry took much interest, was commenced in 1916 under the chairmanship of the late Sir William Matthews, K.C.M.G., and is now under the able and active chairmanship of Mr. M. F. Wilson. The first secretary of this committee was the late Mr. P. M. Crosthwaite, to whom an expression of thanks should not be forgotten for the excellent service he rendered over twelve years, and his work is being continued by Professor J. Purser. Much credit is also due to the assistance rendered by Dr. J. Newton Friend during the course of the research. In addition to large contributions from private sources, the Department of Scientific and Industrial Research have greatly helped by their generous aid in furnishing the Committee of the Institution with considerable sums to assist in this important research. The Committee has already published twelve reports and further ones will be issued as the work proceeds.

It should be added that the iron and steel materials described in the author's paper previously mentioned and now under test as one part of the Committee's extensive research are classified into four main sections :—

Section I—Irons (Rolled and Forged).

(*a*) Wrought iron. (*b*) Swedish charcoal iron. (*c*) "Armco" iron.

Section II—Carbon Steels.

(*a*) Mild steel with low manganese and comparatively high sulphur and phosphorus.
(*b*) Mild steel with 0·70 per cent. manganese.
(*c*) Medium carbon steel with low sulphur and phosphorus.
(*d*) Carbon steel containing 0·40 per cent. carbon.

Section III—Special Steels.

(*a*) Mild steel with 0·50 per cent. copper.
(*b*) Mild steel with 2·00 per cent. copper.
(*c*) Nickel steel containing 3·50 per cent. nickel.
(*d*) Nickel steel containing 36·00 per cent. nickel.
(*e*) Chromium steel containing 13·50 per cent. chromium and 0·36 per cent. carbon, and similar high chromium steel with lower carbon, namely, 0·12 per cent.

Section IV—Cast Irons.

(*a*) Cold-blast cast iron. (*b*) Hot-blast cast iron.

* Important consideration of this subject of corrosion was also given at the XIIIth International Congress of Navigation held in London in 1923, at which the author presented a paper entitled "The Corrosion of Ferrous Metals with Special Reference to their Resistance to the Action of Sea-water."

There is no doubt when the work of the Committee is completed the information obtained will prove to be of the most valuable nature.

Lecture by Sir Harold Carpenter.—The history of the development of stainless steel and iron was also ably reviewed from the scientific and technical points of view by Sir Harold Carpenter, F.R.S., in his recent lectures on "Stainless Metals," *Jour. Royal Society of Arts*, Vol. LXXIX., May 8th, 1931. In the course of these lectures Sir Harold, amongst other most interesting statements, explained clearly and lucidly the wider scope of the use of the term stainless steel as now employed. In view of their valuable nature, some of his conclusions on this important matter are therefore quoted in full :—

"The first extensive industrial application of high chromium steels was in the manufacture of cutlery. Its most conspicuous advantage was resistance to staining by fruit juices and vinegar. It therefore became known as 'stainless steel.' Since this first application the use of high chromium steel has been continually expanding, and the name stainless has been retained. But the word has acquired a somewhat special meaning, and should now be held to include resistance to all kinds of chemical attack, including oxidation at high temperature, solution in acids and pitting in fresh or salt water.

"The original high chromium steels contained at least 0·3 per cent. of carbon, and with this amount in addition to 12 or 14 per cent. of chromium, an air-hardening steel resulted. This steel developed its best properties when in the quenched and tempered state, and was generally used in this condition. When chromium steel containing about 0·1 per cent. of carbon was developed, it was called 'stainless iron' to distinguish it from the harder variety. The use of the word iron in connection with a material that is actually a low carbon steel is not correct, and is liable to cause confusion. It is a pity that the term was ever introduced. An entirely different type of corrosion-resisting alloys, namely, the high silicon cast irons, may also lay claim to the name.

"The stainless steel that was first applied to the manufacture of cutlery was a material of definite properties. It was steel of a particular composition subjected to a certain treatment which developed the mechanical properties required in cutlery, together with a very high resistance to the action of chemicals with which it might come into contact in ordinary use. It had a moderately wide field of application. It could, *e.g.*, be used for the manufacture of all kinds of surgical instruments, but if it had been impossible to vary the mechanical properties without losing the resistance to corrosion the limit of usefulness would soon have been reached. A conspicuous attribute of ordinary steel is the large variation in properties that can be produced by changing the composition and the heat and mechanical treatment. What the engineering world required was a material that would combine this characteristic with a high degree of resistance to corrosion. As a result of further research, this need has been to a large extent met, *and stainless steel cannot now be regarded as a particular kind of steel, but rather as*

a modified form of steel in which most of the mechanical properties of ordinary steel may be reproduced in addition to resistance to corrosion.

"In stainless, as in ordinary steel, the field of selection is broad, and the particular type to be used, and the condition in which it should be used, depend on the mechanical properties required and the chemical action it is expected to resist. Effective utilisation of this new type of material, therefore, requires a knowledge of the phenomenon of corrosion, and the conditions under which it is liable to occur."

With regard to this subject of corrosion and the steel known as stainless, a recent writer in *Nature* has pointed out that "passivity and corrosion resistance appear to be due to the formation of invisible films of oxide, and it is to Mr. Ulick R. Evans that the credit is due to actually isolating such films." He also points out "that the films produced on chromium are continuous and adherent and the addition of that metal to iron therefore greatly increases the tendency to passivity already possessed by it. The corrosion-resisting properties of the high chromium steels are due to this fact."*

Early History of the Metal Chromium.—As regards the metal chromium, it may be mentioned that it was discovered during those troublous times at the end of 1797. Vauquelin, who was described as "Citoyen" Louis Nicolas Vauquelin, read his first paper entitled "Memoire sur une nouvelle substance métallique contenue dans le plomb rouge de Sibérie, et qu'on propose d'appeler Chrôme, à cause de la propriété qu'il a de colorer les combinaisons ou il entre" before l'Institute Nationale on "11^{me} Brumaire, An. VI^{me}," and his second paper, "Sur la nouvelle substance métallique contenue dans le plomb rouge Sibérie, découverte par le Citoyen Vauquelin, et à laquelle il a donné le nom de Chrôme," on the "30^{me} Nivôse, An. VI^{me}" (January 19th, 1798). The discovery was also duly recorded in *Annales de Chimie*, 1798.

Its name in French, "Chrôme," was suggested from the word "chroma" (colour), the "plomb rouge" from which the metal was first extracted being of a characteristic colour, and also from the various and beautiful colours which the oxides of the metal gave to the minerals and substances into whose composition they entered.

Vauquelin confessed that this title did not altogether suit the metal, since in itself it had no particular colour, but the advice of his two friends, "Citoyens" Fourcroy and Hanz, prevailed, and thus we have the designation "chromium."

* An important statement offering full explanation regarding the effect of films will be found on pp. 182–183 in the catalogue of the Faraday Centenary Exhibition at the Albert Hall, devoted to the passive state of metals. It is there shown that Faraday was the first to suggest the theory that passive iron was protected from attack by an invisibly thin film of oxide of iron. The subject is there presented in a clear manner and should be generally of service to those interested in this problem.

Finally the statement by Cuvier with regard to Vauquelin may be quoted, as it is memorable : " Il était tout chimiste, chimiste chaque jour de sa vie et pendant la durée de chaque jour." His different treatises amounted to more than 240.

The value of ferro-chromium and its production as a means of making available chromium steel alloys was first realised by Berthier, who, however, states that he owed his inspiration to Faraday's work on steel and alloys. The following are his words as mentioned in the *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, Vingtième Année (No. CCX), December, 1821: "The idea of introducing chromium into cast steel was suggested to me by the interesting work of Mr. Faraday upon the alloys of various metals with steel; I have made two alloys of cast steel with chromium, one containing 1 per cent. and the other $1\frac{1}{2}$ per cent. chromium."

Faraday, in his paper to the Royal Society in 1822, refers to the foregoing experiments by Berthier, and states that he himself followed on with two experiments, in one of which he produced steel estimated to contain 1 per cent. of chromium and in the other 3 per cent. of chromium. The author has not been able to obtain a specimen of the first-mentioned steel, but he has been able to examine the latter particularly interesting specimen, made about 1820, to which he has given the term "iridescent," No. 28/D.1, in view of its beautiful colour. The analysis of this steel shows the carbon to be 1·59 per cent. and the chromium 2·36 per cent., which is not therefore quite so high as Faraday apparently expected. It should be borne in mind that this was probably the first steel containing chromium ever made in this country. Further information with regard to this specimen is given elsewhere in this book.

A long interval followed before anything of definite or important nature appears to have been accomplished on any practical scale with the metal chromium. Its use was suggested by Mr. Robert Mushet in 1861, later, in 1870, by Mr. A. Parkes, and Mr. H. Bierman, of Hanover, produced ferro-chromium commercially as far back as 1873. The author, however, has always given credit to Mr. Julius Baur, of New York, who in 1865 did much pioneer work with regard to introducing this steel on a practical scale.

Then came the important work by a friend of the author, the late M. Henri Brustlein, of the firm of Messrs. Holtzer & Co., France, and with whom he was associated in metallurgical subjects for many years. Brustlein commenced his experiments on

chromium steel in 1875, and this led to his firm supplying such steel for industrial purposes in 1877. In the author's opinion, it was largely owing to his work that the development of chromium steel on a large scale became possible. Messrs. Holtzer & Co. prepared a valuable exhibit, including chromium steel, for the Paris Exhibition in 1889, which the author well remembers seeing. Brustlein's able work in 1890 was specially recognised by the Société d'Encouragement pour l'Industrie Nationale, who awarded him a prize of 2,000 fr. There was also the work of MM. Boussingault, Carnot, Goutal and Placet.

It was in 1878 that Boussingault gave some interesting information on the subject in a paper which appeared in *Annales des Chimie*, Vol. XV., p. 121, and noted the difficulty of dissolving iron chromium alloys for the purpose of analysis in nitric acid and even in aqua regia.

From the foregoing it will be seen that, starting with the discovery of the metal itself by Vauquelin, France has had a particular and important share in the development of chromium and its alloys.

The Author's Researches on Chromium Steel.—As far as can be ascertained, the first correlated and complete study of chromium steel, that is, such as was possible with the chromium ferro-alloys then available, was contained in the author's paper on "Alloys of Iron and Chromium," presented to the Iron and Steel Institute in 1892. During the preceding two years investigations had been made on a series of fifteen alloys containing from 0·22 to 16·74 per cent. of chromium. Amongst these alloys there were four which may be regarded as the forerunners of the present-day rustless steels; their compositions were as follows:—

	Carbon.	Silicon.	Chromium.
	Per cent.	Per cent.	Per cent.
Specimen L	0·71	0·36	9·18
,, M	1·27	0·38	11·13
,, N	1·79	0·61	15·12
,, O	2·12	1·20	16·74

Many interesting results were obtained from this research, one of them being that largely through the knowledge so gained this country was finally rendered entirely independent of foreign sources for the supply of armour-piercing projectiles, of which

previously large numbers had been obtained from abroad. Such knowledge proved later on to be of immense value in the Great War. An example of what an armour-piercing projectile is capable of accomplishing in the way of perforating thick armour is fully referred to on p. 296. Without chromium it would be practically impossible to obtain the necessary hardness.

Professor Floris Osmond.—Another important fact arising out of the research, and in mentioning this it is with no desire to depreciate the later work of others, is that in the report presented in 1892 by the late Professor Osmond, and forming part of the author's paper previously mentioned, he stated "the etching of Specimen 'L' (0·71 per cent. C., 9·18 per cent. Cr.) with nitric acid may be continued as long as two minutes without sensibly altering the appearance of the sample. The polyhedrons continue brilliant and highly polished." He also added that "as the amount of chromium increases, a compound of iron, chromium and carbon appears to be formed, which is only partially attacked by acid, and possesses great hardness."

From the previous paragraph it is interesting to note that Osmond at the time the author's paper was read in 1892, clearly demonstrated the extraordinary resistance of high chromium steel to the attack of nitric acid.

It will also be observed that Specimen "O" (2·12 per cent. C., 16·74 per cent. Cr.), made in 1892, contained 1·20 per cent. of silicon, an element which is much used to-day for adding to special types of high chromium steel for dies. Whilst the bulk of steels for this purpose used to-day contain lower percentages of carbon, yet it is interesting to note that a well-known maker of motor cars uses a steel containing very high carbon, namely, about 1·50 per cent. with 11 to 12 per cent. chromium.

A modern type of heat- and corrosion-resisting steel used in the form of castings at the present time also contains about 2 per cent. of carbon, the chromium in which, however, is considerably higher than in Specimen "O," though if the amount of chromium which the author aimed for had been present in this specimen, namely, 20 per cent., this steel would have been in line with the modern product mentioned.

In 1904 two series of chromium steels with chromium increasing by steps up to 36·34 per cent., made at the Imphy Steel Works, were examined by Professor L. Guillet, principally from the point of view of their metallographic constitution and mechanical properties. One of the specimens analysed contained 0·14 C. and 13·60 Cr., another 0·38 C. and 14·52 Cr., and a third 0·21 C. and

22·06 per cent. Cr. These resemble the high chromium steels of to-day in their composition.

Modern Developments.—The subsequent development and perfection of rustless chromium steel and the later types of corrosion-resisting steels have been the product of many minds and much research.

Friend, Bentley and West in their paper on "The Corrosion of Nickel, Chromium, and Nickel-Chromium Steels," published in May, 1912, appear to have been the first to have published data showing that chromium steels possessed merits as regards their resistance to the ordinary forms of corrosion by air and water as distinct from acids. They showed that under alternate wet and dry conditions of exposure a 5·30 per cent. chromium steel was corroded at only 21 per cent. of the rate of ordinary unalloyed steel, practically the same figure being obtained for its corrosion in sea water. In tap water the figure was 43 per cent.

From about 1912 to 1914 Mr. Harry Brearley carried out his well-known experimental and practical work on high chromium steels, regarding which Dr. W. H. Hatfield, in a paper on "Stainless Steels," read before the Midland Institute of Mining, Civil and Mechanical Engineers, in 1922, stated that "it was in 1912–13 that Mr. Harry Brearley discovered that the 12 per cent. to 14 per cent. chromium steels, when in the hardened condition, resisted successfully general atmospheric and many other active influences which lead to corrosion." This work was further developed by Mr. H. Brearley, Messrs. Thomas Firth & Sons, and Dr. W. H. Hatfield, to all of whom special credit is due. The Iron and Steel Institute, in 1920, fittingly awarded the Bessemer Gold Medal to Mr. H. Brearley for his research work.

Important developments in the production of these steels on a large scale have since followed here, in America, and on the Continent. The work of Mr. F. M. Becket in America in the development of chromium steels of specially high percentages, also chromium-manganese steels, should be mentioned.

As regards "stainless" steel of the original type, that is, the alloy containing 12 to 14 per cent. of chromium, with percentages of carbon varying from about 0·35 per cent. up to about 0·60 per cent., also steel containing the same percentage of chromium but lower in carbon, 0·10 per cent., and even under, both of these materials have found an increasing field of use, notwithstanding the introduction of the more recent types of nickel-chromium steel. While not so generally resistant to corrosion, the lower cost of these steels makes them of value in certain special cases. Such steels with suitable carbon contents are also specially useful where

abrasive action is experienced, as, for example, in pump rods, and in the large and important application for cutlery, since they have the capacity for hardening and tempering not found in the newer types of chromium-nickel steel. Also for such classes of chromium steel there is the large and important application for cutlery calling for materials possessing non-rusting character.

High Chromium-Nickel Steel

Turning now to high chromium-nickel steel of varying types the development of such steels has arisen out of and been associated with the numerous investigations of the Neo-Metallurgie Co., Messrs. Monnartz, Maurer, Strauss, Gruner, Haynes, Brearley, Messrs. Firth-Brown, Dr. W. H. Hatfield, Messrs. Brown Bayley's Steel Works, Ltd., Mr. J. H. G. Monypenny and others.

Those who are interested in the history of the development of non-rusting steels are referred to two papers by German contributors, one by Dr. Monnartz, which appeared in the German publication *Metallurgie*, of March, 1911, and the other by Dr. E. Maurer, who contributed a paper of special interest, entitled "The Maurer Manganese Steel in the Development of Non-Rusting Steel," to the Eisenhütten-Institut of the Sächsischen Bergakademie, in August, 1929. These two papers give useful information on this important subject.

Much valuable research work as well as practical applications of these classes of steel have also been carried out in France by La Société Anonyme de Commentry Fourchambault et Decazeville, including the important special investigations by Messrs. Dumas, Guillaume, Chevenard and others at the famous Imphy Works of that company. As early as 1906 four series of nickel-chromium steels of high and low carbon, with chromium content up to 20 per cent., and nickel up to 30 per cent., were prepared at these works, their metallographic constitution and mechanical properties being investigated by M. Guillet. In addition to their own previous work on chromium-nickel steel the author's firm, La Société Anonyme de Commentry Fourchambault et Decazeville, of France, and Messrs. The Midvale Steel Co., of Nicetown, Pa., U.S.A., now collaborate and unite in developing this and other special alloy steels under their group of patents and manufacturing practice.

It may be interesting to add that one of these types of steel known as A.T.V. (Acier Turbines à Vapeur) is to be used for the complete blading equipment of the turbine engines which are to propel the new mammoth French liner *Super-Ile-de-France*, stated to have a length of 1,017 feet with a beam of 115 feet, and a designed output of propelling equipment of 160,000 s.h.p.

Production in U.S.A.—The makers in America have shown great

enterprise in the manufacture and utilisation of these improved chromium-nickel steels for many purposes. Some time ago the author obtained important information with regard to the magnitude of production of these types of steel. In the latest statistics available, presented in America by the *Iron Age* (December, 1929), it is stated that in that country the output of open hearth and electric chromium steel in ingots and castings amounted to 311,700 tons; to this should be added chromium-nickel steel 261,600 tons, thus a grand total of nearly 600,000 tons of non-corroding steels. It will be seen, therefore, that the use of these materials is on a most important scale.

Amongst others, a full account by the author of the history of these developments will be found in his introductory address, entitled "The Corrosion of Steel Alloys," when presiding at the meeting on the "Corrosion of Metals; Ferrous and Non-Ferrous," held by the Faraday Society in 1915, and in the discussion which then took place; also in Chapter X. of the author's book *Metallurgy and Its Influence on Modern Progress*, published in 1925; and in his article on "Special Steels," which appeared in *Pitman's Engineering Educator* for March and April, 1927.

Application of High Chromium-Nickel Steel.—A more detailed description and reference to some of the applications will now be given.

The most generally used types of high chromium-nickel steel are low in carbon and contain from 15 to 22 per cent. of chromium, with 7 to 14 per cent. of nickel. Such alloys have a specially wide range of resistance to corrosion, and overcome many of the difficulties experienced in the chemical industries. The technique of their production has now been fully established, making them available in all the various forms required, including castings and forgings, rolled sheets and bars, tubes and wire. With suitable modification of machining methods they are also readily machinable. In view of the extended use of welded constructions, it is also satisfactory that each of the several welding methods can be applied to these alloys, the process being in all cases of an autogenous character. Cold working causes hardening, which can be removed by heating to 950° C. followed by a quick cooling. The softest condition is brought about by a rapid cooling from 1100 to 1200° C. The high chromium-nickel steels containing from 15 to 20 per cent. of chromium with 7 to 10 per cent. of nickel are used successfully in a great variety of apparatus for chemical manufactures.

To enumerate the chemical media to which the new types of steel are resistant would require more space than is here available,

their number so far ascertained being very large, while it is being added to daily as further experience is obtained. Generally their resistance to fermentation products has been demonstrated on a practical scale in breweries, and it has been shown that there is no trace of corrosion from stale beer or adherence of sedimentary matters. Attack does not occur when exposed to boiling vinegar or the vapours therefrom, and their resistance to acetic acid of all strengths and temperatures is a valuable property. Although there is some range of choice among steels which will withstand nitric acid provided care is taken in the manufacture, yet those of the chromium-nickel type are more reliable than the simple chromium steels. Such steels can be made quite resistant to liquid nitric acid or the fumes from it, and are being used in such parts as pump rods, impellers and fans. They are also not affected by the mixed nitric and sulphuric acid used, for example, in the manufacture of explosives.

Many difficulties and complex problems arise in the manufacture of artificial silk, but alloy steels are available resistant to most of the solutions employed in the various processes.

Non-corroding steels have been employed in the oils and fats industry, and there are many directions in which their use may be extended with advantage, in the manufacture of soap or candles and the preparation or refining of edible fats both neutral and synthetic.

Pans, tanks, containers and chemical plant generally made from these steels possess many advantages in the operations of crystallising various salts, including, for example, potassium nitrate, Glauber's salts, sodium sulphate and sodium ferrocyanide.

Notwithstanding the great range of applicability of chromium-nickel steels of the type already indicated, there still remain special problems of corrosion which they do not adequately meet. It has been necessary, therefore, to develop further and more special types, among which material containing small additions of other elements such as tungsten, molybdenum and copper may be selected for mention, one of the advantages of which is that it is not appreciably attacked by dilute solutions of sulphuric acid. This fact makes it specially suitable for use in the sulphate house of coal and coke by-product recovery plants, as, for example, in the centrifugal separators or belt driers.

This steel is further of special utility in the food industries, being unaffected by the dilute solutions of phosphoric acid contained in chemical foods. This characteristic and its resistance to acid calcium phosphate, and nearly all the other chemicals employed, make it of value in sugar refinery plants, where breakages occa-

sionally occur, owing to the corrosion of unsuitable materials. In one particular plant this high chromium-nickel alloy steel is being used for handling the phosphoric acid at a concentration of 1·7 sp. gr. at a working temperature of 120° C., and also for the equipment used in the concentration of the dilute acid.

Many chemical and distillation processes are carried out at temperatures well above red heat, thus calling for heat-resisting characteristics in the structural materials, as well as chemical inertia. Some examples of these are given on p. 292, in the section on Heat-Resisting Steels. Finally, amongst the applications of high chromium-nickel steel, present and prospective, may be mentioned sheets for the bodywork, shields, and wheel discs of motor cars, seamless tubes, wire, drop forgings, and utensils, accessories, and fittings of all descriptions where a high finish and resistance to corrosion are required.

In addition to the various materials already mentioned, there are various other alloy steels resistant to special forms and conditions of corrosion.

Specially interesting, and a sign of the times, is the use made of non-corrodible steels of these newer types in the preservation of St. Paul's Cathedral, London.

Tie rods made from ordinary steel or wrought iron would doubtless have lasted many years before their eventual destruction by corrosion, but the committee responsible for this important work did not wish to put any such limitation upon their endeavours, specially in view of metallurgical progress, which had indicated that corrosion need not be regarded as an inevitable evil. Considerable use has therefore been made of the new steels. The reinforcements now consist of tie bars, 3 and 4 inches in diameter, of high chromium-nickel steel having a tenacity of 45 to 50 tons per square inch, with cast couplers and wall plates of the same material. They replace those originally used by Sir Christopher Wren, F.R.S., made from wrought iron. Large applications of this steel are taking place in the United States, our own country and elsewhere for certain parts of building construction.

Steels for Steam Turbine Blades and Steam Fittings

With the ever-increasing demand for higher temperatures and pressures in the operation of steam turbines, there has arisen a need for steel which retains not only considerable strength at high temperatures but also marked resistance to corrosion and considerable hardness to withstand the erosive action of wet steam. The degree of resistance to corrosion is a particularly

important consideration in marine turbines and in land turbines situated near the coast and elsewhere, where salt water may, by one means or another, find its way into the turbine.

Steels containing 3 to 5 per cent. nickel have in the past been used extensively for the blades of steam turbines, and, in some cases, with very satisfactory results. In other cases, particularly in marine turbines, trouble has been experienced due to corrosion; this also occurs at the low-pressure end of some land turbines, where a certain amount of corrosion takes place. Periods of disuse are found to result in increased corrosion.

The use of bronzes of various kinds, while dealing successfully to a large extent with the corrosion problem, did not prevent the effects of erosion, and these materials are unsuitable for superheated steam. High chromium steel, often called stainless, although this term is not strictly correct, has proved of value against both erosion and corrosion in many cases, and, in fact, considerable quantities of this steel are being used for turbine blading. It does not, however, provide the complete solution desired in many instances; where there is any liability to contamination of the steam it becomes badly corroded. With advancing steam temperatures also it has its limitations, and the need for heat treatment and the preparation of a smooth surface are disabilities which introduce difficulties in its use in turbine construction, also limiting the constructional processes which can be employed, since these must not in any way be allowed to upset the heat treatment.

By the association of Messrs. Commentry-Fourchambault et Decazeville and Messrs. Hadfields, also later Messrs. The Midvale Steel Company, the steel known as "ATV" has been successfully developed and is being used on a considerable scale for steam turbine blading and fittings. Important experience in large installations over several years has proved the special suitability of the material for these purposes.

This "ATV" type of steel is a nickel-chromium alloy of iron having a high percentage of nickel, from 30 to 36 per cent., is completely non-corrodible under all conditions experienced by steam turbine blading, and is highly resistant to erosion. Further, it retains excellent mechanical properties at the highest steam temperatures, as shown by the figures on p. 291.

Its character remains unaffected in superheated steam, even at 600° C. (1,110° F.). In this way it is definitely superior to the nickel-copper alloys which suffer intercrystalline breakdown under such conditions. "ATV" is also lighter than the nickel-copper

Temperature.		Tensile Strength.			
°C.	°F.	Yield Point. Tons per square inch.	Maximum Stress. Tons per square inch.	Elongation. Per cent.	Reduction of Area. Per cent.
15	60	30	50	20	35
450	840	26	42	18	28
500	930	24	39	20	30
600	1,110	17	26·5	24	35
650	1,200	14	20·5	27	52

alloys, resulting in correspondingly lower centrifugal stresses, while its coefficient of expansion of 12·8 millionths per 1° C., being not markedly different from that of the ordinary or nickel steel used for the rotors, also prevents troubles due to excessive relative expansion.

As the direct outcome of the satisfactory performance of "ATV" blading in several turbines installed in a large Continental generating station since 1920 and 1922 respectively, notwithstanding the fact that the steam was badly contaminated by salt and thus adding to the severity of the test, turbine blades of this alloy steel are now being used on a large scale by British, European and other navies. In fact, altogether, turbine plants developing about 2¼ million horse-power are now equipped with blading of this steel.

Similar satisfactory results were experienced with "ATV" blading in a 50,000-KW. turbine in the Gennevilliers power station near Paris, where the steam at the turbine inlet is at 400° C. (750° F.) and a steam pressure of 255 lb., which have led to this material being further used in turbines at this and associated stations.

In the 85,000-KW. plant of the Imperial Chemical Industries Ltd., at Billingham, "ATV" steel is employed for the rows of the turbine blading subjected to the most severe conditions, that is at the high pressure end of the primary turbines. These turbines are required normally to operate with steam at 630 lb. per square inch gauge and at a temperature of 433° C. (833° F.), exhausting at a pressure of 275 lb. per square inch gauge.

Through the kindness of Imperial Chemical Industries Ltd., and of the makers of the turbine plant, Messrs. The Metropolitan Vickers Electrical Co. Ltd., the author is able to show a portion of this plant in Plates LVI. and LVII. Plate LVI. shows the

primary turbine rotor and Plate LVII. one of the three primary turbines.

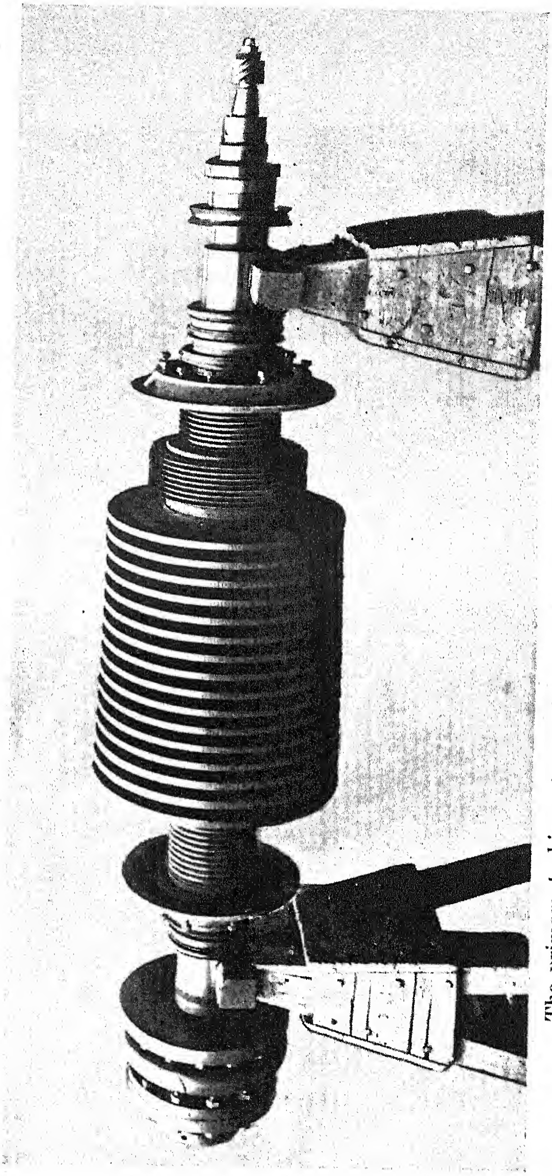
The same type of steel has also proved highly satisfactory not only for blading and nozzles but for spindles and seats of valves, springs and other applications in which highly superheated steam is used.

While engineers have hitherto been inclined to regard "ATV" steel as an excellent material to be utilised in special cases where high steam temperatures, or excessive corrosion or erosion are encountered, it is becoming increasingly clear that it is also economical in more ordinary installations. Even where apparently no better materials are needed than nickel steel or bronzes, the use of "ATV" steel is amply justified by the saving resulting from the maintenance of efficiency and the avoidance of periodical replacement.

Heat-Resisting Steels

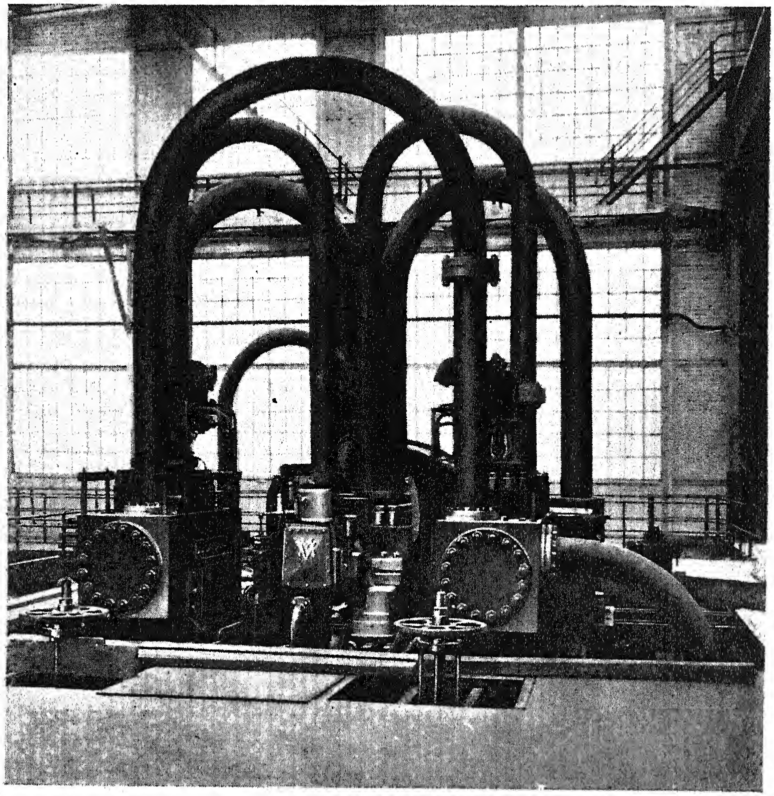
The term "heat-resisting" steels is applied to special steels which resist oxidation or scaling and other forms of corrosion at high temperatures while also retaining a high degree of mechanical strength. There have been marked advances in the production and application of these materials during recent years. They have proved of great assistance to engineers and others in improving practice and enhancing efficiency and economy by the use of increased temperatures in boiler, furnace and steam work; also in regard to the mechanical operation of furnaces, the increased robustness resulting from their substitution for refractory materials, and so on. These steels are, in general, ferrous alloys with high nickel and chromium contents, variable in amount according to the uses and properties demanded. The addition of other elements, such as silicon and tungsten, in comparatively small proportions, has been found beneficial in special cases. The iron content of some of the later products barely exceeds 50 per cent.

High-chromium steel possesses useful characteristics in regard to maintained strength, and scaling to a much less degree than ordinary steel up to moderately high temperatures. Such steel therefore finds useful applications, as in valves for automobiles, but these applications are limited, because the desired qualities are not retained far enough to meet the full demands of engineering practice. The strength of this steel falls away rapidly at temperatures above 650° C., and it practically loses its non-scaling characteristics at 850° C. Consequently, for example, it is unsuitable for the valves of high-duty aeroplane engines, or for such articles as



The primary turbine rotor made by the Metropolitan-Vickers Electrical Co. Ltd., for the Imperial Chemical Industries Ltd., Billingham plant. For the rows of turbine blading subjected to the most severe conditions "ATV" steel is employed.

[*To face p.* 292.



One of the three primary turbines made by the Metropolitan-Vickers Electrical Co. Ltd., for the Imperial Chemical Industries Ltd., Billingham plant. The normal rating of the machines is 11,900 K.W., the speed being 2,400 r.p.m., with steam at 630 lbs. With a maximum steam pressure at the turbine of 650 lbs., the maximum load could be increased to 12,500 K.W. The "ATV" steel is employed for the rows of turbine blading subjected to the most severe conditions.

the boxes in which steel parts are heated with their carbonising mixture for case-hardening, the temperature in this instance reaching 1,000° to 1,100° C.

The addition of silicon, in amounts up to about 3 per cent., has been found to produce a marked improvement in high-chromium steel, especially in non-scaling characteristics, and in addition to improve its strength to some degree at high temperatures. Beyond, however, about 800° C., the qualities are still below practical requirements in many directions.

Prolonged research by the author's firm, Messrs. Hadfields Ltd., Sheffield, in collaboration with the famous French firm Société Anonyme de Commentry-Fourchambault et Decazeville, Imphy, and later with the Midvale Steel Co. of U.S.A., has resulted in the evolution, amongst others, of the type of high percentage nickel-chromium steel known as "Era/ATV," which has quite exceptional strength and non-scaling properties at high temperatures, while still being of reasonable cost. This steel is used at bright red heat and under high centrifugal and other stresses in the rotors of exhaust gas turbines working at a temperature of 800° to 930° C. and speed of 30,000 r.p.m., or even 50,000 r.p.m. on test; and it has proved itself more than equal to the highest requirements yet imposed by the designers on the exhaust valves of motor car and aeroplane engines.

The truth of this claim is amply demonstrated by the fact that valves of "Era/ATV" steel have been used in machines which have won for England speed records on land, water and in the air. This refers particularly to the Supermarine-Napier S5, which won the Schneider Trophy, at 281 m.p.h., in 1927; to the Gloster-Napier, which was entered for the trophy in 1929; to Sir Henry Segrave's *Golden Arrow* and Captain Sir Malcolm Campbell's *Bluebird;* and to Sir Henry Segrave's motor boat *Miss England*, as well as to Mr. Kaye Don's *Silver Bullet.*

Whereas ordinary steel, having a tensile strength of 30–35 tons per square inch at normal temperatures, loses four-fifths of this tenacity at 800° C., the tensile strength of "Era/ATV" steel at this temperature is $21\frac{1}{2}$ tons per square inch, or more than three times that of ordinary steel. Fortunately, the properties of maintained strength and freedom from scaling at high temperatures are combined with satisfactory qualities of machinability and general amenability to manufacturing processes.

For cases where the conditions of service are not so severe, there are various alloy steels not quite equal to "Era/ATV" in their capabilities, but of great merit and somewhat less expensive. The

silicon-chromium "Hecla/NS" steel, for example, is used in many high-duty engines, and the production of valves of this type by the author's firm now exceeds one million. Valves of this steel were used in the winning Bentley car in the race for the Grand Prix d'Endurance at Le Mans in 1927, 1928, 1929 and 1930. Another of the Hadfield heat-resisting steels, "Era/HR," was employed for the valves of the new Talbot cars finishing third and fourth in the Grand Prix, 1930.

Modern heat-resisting steels enable important advances to be made in the operation and maintenance of furnaces of all kinds. In the case of mechanically stoked furnaces on a certain cargo vessel, for example, operating with air preheated to 310° F., component parts of cast iron had to be replaced after every second round trip between Canada and this country. After adopting "Era" heat-resisting steel for all the parts exposed to the most severe conditions, the grate was found to be in perfect condition after one year's continuous service.

Quite large castings are now being made in this type of heat-resisting steel, weighing up to 6 or 8 tons each, or more. Castings of this material, 3 inches in thickness, are used as reaction vessels in a Bergius coal-hydrogenation plant. The coal substance is converted into an oil having the consistency of tar at a temperature of nearly 500° C. (930° F.), and a working pressure of upwards of 3,000 lb. per square inch. The "Era/HR" steel is also used successfully for parts of tar distillation plants, including heater tubes for tar stills. In one case the pipes exposed to temperatures ranging from 950–1,250° C. (1,740–2,280° F.) have lasted nearly a year of continuous working.

With recuperators built up from castings of heat-resisting steel much more efficient heat transfer is accomplished between the waste gases and the air which it is desired to preheat; also such castings are, of course, much less fragile than clay tubes.

While, as in the examples already given, most furnace components suitable for the adoption of heat-resisting steel lend themselves to production in the form of castings—and it is desirable to use castings where possible on the score of cost—in other cases it is quite possible to manufacture articles in heat-resisting steels in the form of forgings, or built up from rolled sheets. Welded constructions may also be employed where this is desirable.

High-Speed Tool Steels

An essential requirement in a high-speed steel is that the metal should retain its strength, toughness and hardness at a high tempera-

ture. As a necessary corollary the steel must be self-hardening, *i.e.*, it must harden when cooled in air without quenching. Tungsten is particularly useful in conferring these properties, and is consequently the alloying element present in greatest quantity in high-speed steels.

It is not too much to say that the introduction of high-speed tool steels has revolutionised machine-shop practice, and contributed to an essential degree in the evolution of present-day civilisation. Whereas cutting tools of ordinary carbon steel commence to soften below 200° C., and are thus restricted to light cuts and moderate feed, high-speed steel of the most modern type retains its strength and hardness at red heat and makes possible heavy cuts and rapid feed.

The first air-hardening tool steel, evolved by Mushet about the year 1868, made possible about 50 per cent. higher cutting speeds than could be used with ordinary high-carbon steel. It was found that by suitable heat treatment the cutting power of the Mushet alloy of modified composition could be greatly increased. Experiments led also to the discovery that a superior alloy, more easily worked than the original Mushet steel and capable of about four times the cutting speed of the latter, could be made by raising the tungsten content, using chromium instead of manganese, and reducing the carbon content. A typical high speed steel about twenty years ago, therefore, contained 0·6 per cent. of carbon, 0·12 per cent. of manganese, 0·05 per cent. of silicon, 3·44 per cent. of chromium, and 17·25 per cent. of tungsten. Innumerable high-speed tool steels have since been produced by different workers, some containing up to 2 per cent. of vanadium, up to 5 per cent. of cobalt, and a small percentage of molybdenum. According to the feed, cut and quality of the material worked upon, cutting speeds from 250 to 500 feet per minute have been made possible, resulting in from ten to twenty times the speed of machining attainable with carbon-steel tools. As already mentioned, tungsten is the principal alloying element in modern high-speed steels, a typical analysis being: carbon, 0·62 per cent.; manganese, 0·10 per cent.; silicon, 0·18 per cent.; chromium, 3·75 per cent.; tungsten, 16·5 per cent.; vanadium, 1·0 per cent. The inclusion of vanadium is found to increase the durability of the tool under heavy working conditions, and to give an appreciable increase in cutting efficiency.

One of the latest and most remarkable developments in tool steels is the alloy already mentioned on p. 267, containing no fewer than nine elements, namely, iron, carbon, manganese, chromium, nickel, tungsten, cobalt, vanadium and molybdenum. This

material represents a most important advance because, apart from its other applications, it enables manganese steel to be machined, thus facilitating the use of this valuable alloy for many parts which have hitherto been difficult to make.

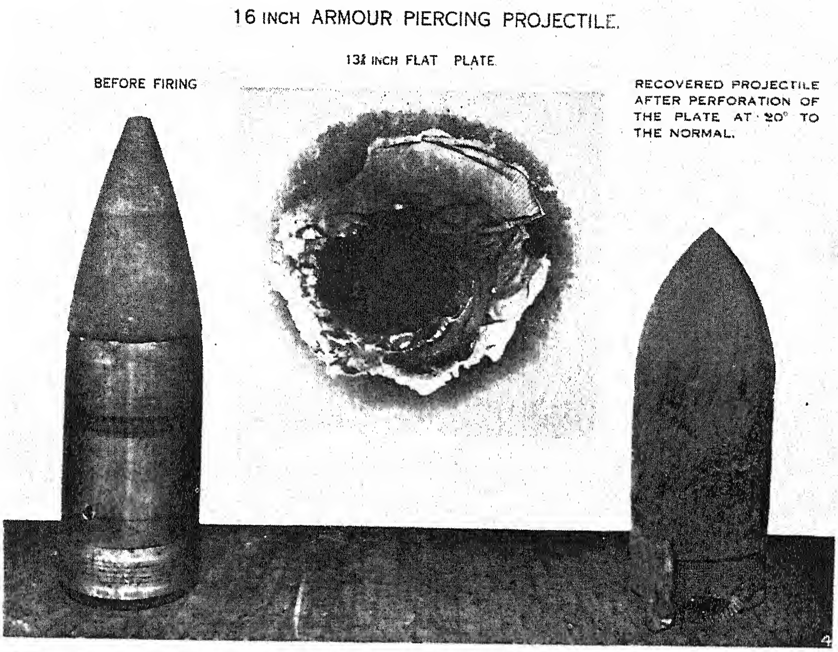
Steels for Armament Purposes

It is obviously impossible to give precise information concerning the composition of steels used for modern armament and ordnance. It may, however, be said that alloy steels play a vital part in all the means and instruments of defence and offence. Happily, too, the development of alloy steels for the purposes of peace has been largely assisted by research and experience in their application to war material.

About forty years ago, at quite an early stage in the author's work upon the alloys of iron and chromium, some remarkable results were obtained with chromium-steel in armour piercing projectiles made by his firm. This work was fully described in his paper on *Alloys of Iron and Chromium*, presented to the Iron and Steel Institute in 1892. A 6-inch projectile of this type was fired through a 9-inch compound plate. Being uninjured, it was ground up, fired a second time, and again penetrated uninjured another 9-inch compound plate. Needless to say, these encouraging results were a great incentive to further efforts; specially, too, as just previous to that time the British Government had found it necessary to procure certain supplies of armour-piercing projectiles from abroad. The work thus commenced has been carried on ever since with such success that the armour-piercing projectiles now made by the author's firm are capable of passing unbroken through the thickest armour afloat.

Nickel steels containing 5 per cent. or more nickel and 0·3 to 0·4 per cent. carbon are highly resistant to shock, and these alloys have been used for the shield plates of field-guns and for other purposes where resistance to impact is required. Nickel-chromium steel, when suitably treated, develops hardness, toughness and strength, thus making it useful for armour plates, but the possibilities in this direction have been surpassed by the penetrative powers of the latest armour-piercing projectiles.

This type of Hadfield armour-piercing projectile of 15-inch or 16-inch calibre is able to pass completely through a hard-faced armour plate 12 inches, 14 inches, or even 16 inches in thickness, not merely normally, but with the plate inclined 15°, 20°, and even 30°, and to remain unbroken. In a typical case, the projectile fired at a velocity of about 1,750 foot seconds, equivalent to 1,200 miles



HARD-FACED ARMOUR PLATE 14 IN. IN THICKNESS, INCLINED 20°, PERFORATED BY A 16 IN. CAPPED ARMOUR-PIERCING PROJECTILE IN ·00314 OF A SECOND.

[To face p. 296

per hour, passed through a 12-inch plate in 0·0039 of a second, and was recovered unbroken. The amount of energy absorbed in accomplishing this task was about 25,000 foot tons, and 720 lb., or $1\frac{1}{4}$ cubic feet, of metal had to be displaced in about four-thousandths of a second. Plate LVIII. shows the result of a proof trial of one of these large calibre shells 16 inches in diameter, after passing through a hard-faced armour plate $13\frac{5}{8}$ inches in thickness and inclined 20°.

As can be readily imagined, the capabilities of steel and the steel-maker are taxed to the uttermost in the production of armour-piercing projectiles, and, though we all deplore war, it has to be admitted that the continual striving for better armaments has at any rate contributed greatly to the advancement of the metallurgy of steel.

Special Structural and High-Tenacity Steels

In the space here available it is impossible to do more than outline the nature and application of the many special steels which have been developed for general engineering and constructional purposes. The complexity of the subject is increased by the fact that, in some instances, ternary and quaternary alloys have been found most suitable for special purposes. Also, further advances are continually being made, new alloys appearing in almost bewildering number. As Faraday truly remarked, there is " an infinity of different metallic combinations to be made," and we are still far from having made and examined them all. There are, however, already special steels available for almost every requirement, and the steel user may rest assured that the metallurgists of to-day are both willing and able to supply materials specially suited to any conditions, however difficult.

Leaving out of consideration manganese and silicon steels, which have already been fully discussed, high-tenacity engineering steels are mainly, but by no means invariably, of the chromium, nickel, or nickel-chromium type, sometimes with the addition of other elements.

Nickel steels are particularly valuable for structural purposes, the addition of nickel to carbon steel resulting in an increase of strength, ductility and toughness, and a higher ratio of elastic limit to ultimate strength. Steels containing from 2 to 4 per cent. of nickel and from 0·2 to 0·5 per cent. of carbon are used extensively for constructional purposes. Their applications include machine and engine parts, seamless tubes for bicycles, etc., the frames of large dynamos, gun and marine forgings, special shafts and

axles, and the members of large bridges or other structures in which the superior mechanical properties of the alloy steel outweigh its higher cost as compared with simple carbon steel.

The addition of chromium, in the presence of carbon, to steel has the effect of hardening the metal, and reducing the tendency to granular structure. In conjunction with nickel or vanadium, this element gives alloys which are exceptionally strong and resistant to wear, yet can be machined easily. Such steels are therefore employed for high-class gearing, the crankshafts of internal-combustion engines, and other special parts of machines.

Where wear and abrasion are the primary considerations, apart from manganese steel, ordinary chromium steel with a comparatively low percentage, 1 to 2 per cent., of this element has proved itself of considerable service in the form of both castings and forgings. A high-tenacity steel, hard, tough, and resistant to wear, suitable for use in the balls, rollers and races of ball and roller bearings, contains about 0·8 to 1 per cent. of carbon and 1·2 to 1·6 per cent. of chromium. Its ultimate strength may be as high as 130 tons per square inch, when the metal is suitably heat-treated, correct heat-treatment being essential to the development of the advantageous properties of chromium steels.

Steels with higher percentages of chromium have remarkable powers of resistance to corrosion, as already mentioned on pp. 287 to 292. The advantages of using non-corrodible steel for bridges and other civil-engineering structures is receiving serious attention because, apart from the great annual expenditure in their maintenance by painting and other means of protection, constant and alert supervision is necessary, after a period of years, to ensure that corrosion is not undermining the structure at some vital point. There can be no doubt that alloy steels will be used to an ever-increasing extent in even the heaviest engineering constructions, such as bridges, ships, and so on, wherever specially difficult requirements of stress, corrosion or other conditions have to be met. Considerations of expense and the necessity for proceeding cautiously with the use of new materials in such large structures will make the rate of progress slower than in smaller constructions, but developments in this direction have already commenced, and they will not cease. Alloy steels, when properly selected and properly treated, can be used under abnormally difficult conditions with as high a factor of safety as ordinary mild steel under its usual working conditions.

The combined effect of nickel and chromium in nickel-chromium steels is to produce a material with excellent physical properties,

well suited to a great variety of structural applications. According to the conditions to be met, from 1·25 to 3·0 per cent. of nickel and from 0·6 to 1·25 per cent. of chromium are employed, the ratio of nickel to chromium being approximately 2½ to 1, and the percentage of these elements being higher for higher working stresses, particularly in regard to dynamic loads. The general effect of nickel and chromium when used together is to raise the elastic limit of steel and increase its ductility, hardening power, and resistance to wear. Heat treatment is required to develop fully the properties of these alloys, and maximum strength combined with satisfactory ductility is obtained in the air-hardening steels which contain more than 5 per cent. total of nickel, chromium and carbon. The high qualities obtainable in alloys of this type are exemplified by a nickel-chromium steel recently made by the author's firm with the following properties: tenacity, 108 tons per square inch; elastic limit, 90 tons per square inch; elongation, 15 per cent. with 51 per cent. reduction of area; ball hardness, 477; and Frémont shock test, 5·3 kg.-m. with 70-degree angle of bend. The high value of the impact test figure is indicative of the dynamic strength which makes nickel-chromium steel so useful for parts which have to resist shock and live loads.

The comparative cheapness and easy machinability of nickel-chromium steels are strong points in their favour, and these alloys are used satisfactorily in automobile construction, for bridge girders, and for gearing and other special components, as well as for armament purposes.

The remarkable results obtainable from modern special steels are not simply the results of alloying. They represent the combined effect of special chemical composition, together with refinements in manufacture and treatment reached, in most cases, only after a long series of costly experiments. A useful example of this is to be found in the results of a series of tests carried out in the Hadfield Research Laboratories on a number of nickel-chromium steels, heat-treated to give Brinell ball hardness numbers ranging from 200 to 600. Throughout this wide range, this improved steel was from 100 to 200 per cent. more resistant to impact than material coming under the designation of ordinary good quality steel. As regards resistance to repeated impact, nickel-chromium steel containing 0·64 per cent. carbon and 0·08 per cent. sulphur and phosphorus together withstood 60,000 blows before fracture; whereas a specimen otherwise similar in composition but of the improved type of steel, containing only 0·027 per cent. of sulphur and phosphorus together, withstood 167,000 blows without

fracture. The conditions of testing were the same in both cases, and the ball hardness was 600 for both specimens.

This extraordinary increase in toughness and resistance to shock, vibration and fatigue, without any sacrifice of tensile strength, represents the outcome of special metallurgical experience extending over nearly half a century.

A bar of one of these Hadfield nickel-chromium steels, $1\frac{1}{2}$ inches in diameter, having a ball hardness of as high as 410, was bent double over a radius of $1\frac{1}{4}$ inches without breaking. A tensile test taken from an adjacent portion of the same bar gave the following results; yield point, 86 tons per square inch; maximum stress, 91 tons per square inch; elongation, 13 per cent.; reduction in area, 47 per cent. This is a remarkable instance of high ductility and toughness accompanied by high elastic limit and tenacity.

The use of molybdenum as an addition to nickel-chromium steel has been found to confer further advantages by enabling the same degree of toughness to be obtained in parts of comparatively large section, as in the smaller sections. Thus in bars of this nickel-chromium-molybdenum steel, 4 inches in diameter, and with a Brinell hardness of 330, tensile characteristics are obtainable as follows: yield point 60 tons and maximum stress 70 tons per square inch, with an elongation of 20 per cent. and reduction of area of 60 per cent. These figures are accompanied by an Izod impact value as high as 50 ft. lbs. With ordinary nickel-chromium steel there is a falling off in toughness in the larger sections as compared with the smaller ones. It is an indication of the confidence which may be placed in modern high tenacity steels of this type that railway companies, which have necessarily to proceed cautiously, are adopting such material in the connecting and coupling of rods of their latest locomotives.

There are many other special steels which might be mentioned in relation to engineering and constructional applications of all kinds, but it is impossible here to do more than refer to a few of them.

The addition of 1 or 2 per cent. of manganese increases the strength of carbon steel and, in conjunction with appropriate heat treatment, gives other desirable properties. The applications of these intermediate manganese steels—which must not be confused with the author's manganese steel containing about 13 per cent. of manganese—include axles, tyres, shear blades, and other parts demanding strength and resistance to shock.

Steel containing $1\frac{1}{2}$ to $1\frac{3}{4}$ per cent. of manganese, with comparatively low carbon, has proved valuable in the manufacture of

fish-tail bits used in rotary drilling, also for core barrel cutter heads. With such steel a Brinell hardness of 550 to 575 is obtained on the cutting edge by quenching, and, in the products for which this hardness is suitable, the results obtained are much superior to those with ordinary carbon steel. Another successful application of intermediate manganese steel has been for parts of mining machinery and many other engineering purposes since the author first introduced it some twenty-five years ago.

Yet another instance of the value of that remarkable metal manganese is to be found in its presence in silico-manganese steel. This alloy has been shown, by many lengthy and costly researches, to offer advantages over other types in its application to the manufacture of laminated springs.

Among other special elements employed as additions to steel, mention should be made of molybdenum, vanadium and titanium.

The use of molybdenum for alloy steels has increased considerably in recent years, as its presence in comparatively small amounts is found to have a beneficial effect upon the properties of high tensile nickel-chromium steels and increasing the toughness of this steel. It has been found in some cases that with ordinary nickel-chromium steel it is not easy to obtain adequate toughness in comparatively large masses, that is comparable with that obtained in small bars. Molybdenum also overcomes the difficulty by intensifying the hardening effect on quenching of the steel under treatment, its presence enabling the hardness to penetrate to a greater depth and thus give greater toughness to the steel when tempered. A further advantage obtained from the use of molybdenum in nickel-chromium steel containing under about 0·60 per cent. of that element is that its addition avoids to a large extent what is known as "temper brittleness," that is it prevents the occurrence of brittleness found in this steel when cooled slowly from the tempering operation after hardening.

Nickel-chromium-molybdenum steel also has much improved strength in the higher range of steam temperatures now employed, and is therefore finding an increasing use for such purposes in the flange bolts of steam pipe lines.

When correctly heat treated chromium-molybdenum steel develops high mechanical properties, and alloys of this type are used for such purposes as the manufacture of aeroplane frames. Molybdenum is therefore proving to be a useful element as an addition to several classes of steel.

Vanadium is a valuable constituent of the most modern types of high speed tool steels, its addition having effected a considerable

improvement over the earlier ordinary tungsten-chromium steels. This element is used to a considerable extent in America as an addition more specially to chromium steels in their use as high tenacity steels ; improved toughness is claimed for its use.

The general effect of vanadium in conjunction with proper heat treatment is to improve the physical structure of steel and increase the resistance of the metal to shock and fatigue. Such alloy steels are employed successfully for special shafts, gears, and tools for punching, shearing, drawing and other purposes. Chromium-vanadium steel possesses high mechanical strength and resiliency, and is capable of withstanding severe shock and impact. It is therefore often used for the frames and axles of motor cars, and many similar purposes.

Titanium, which is also used to a greater extent in America than in this country, is stated to be of service in conferring soundness on certain types of steels, and is also used as a purifying agent.

Similar improvements to those above mentioned are also claimed for the use of zirconium.

Copper is being used as an addition both to carbon and alloy steels, an interesting recent application being in connection with the hardening property it confers on steel when subjected to tempering. For example a steel containing 0·10 per cent. carbon and 1·00 per cent. copper when suitably tempered may have its yield point raised to double its original value. This is further proved in an interesting paper on this subject, together with a most useful bibliography, recently presented to *The Iron Age* (September, 1931) by Mr. H. B. Kinnear, Consulting Metallurgist, of Marion, Ohio, aided by Professor D. J. Demorest, professor of metallurgy at the College of Engineering, Ohio State University, Columbus, Ohio, with regard to copper steels. The research deals with a range of copper contents from 0·50 up to 4·98 per cent., the carbon varying from 0·29 to 0·41 per cent. One of the conclusions arrived at by the research is that heat treated steel containing 1·00 per cent. copper combines both high elastic ratio and ductility.*

Alloy Steels Possessing Special Magnetic Qualities

Under this heading brief reference may be made to a number of interesting alloy steels possessing remarkable magnetic qualities. To the uninitiated it might appear that such qualities are of no great importance, but this is far from being the case. The efficiency of modern ignition magnetos depends largely upon the use of improved permanent magnets of alloy steel ; long-distance telephony owes its present development largely to the availability of

* A paper of similar interest was recently contributed to the Iron and Steel Institute by Dr. J. Newton Friend and Mr. W. West on "The Resistance of Copper-Nickel Steels to Sea Action."

alloys of specially high permeability; and many other examples could be given.

One of the most remarkable properties of the Hadfield manganese steel is that it is non-magnetic, although it contains about 86 to 88 per cent. of iron. For this reason portions of the structure of warships near the compass position are often made of manganese steel.

Formerly, permanent magnets were almost invariably made from high-carbon steel containing 1 to 1·5 per cent. of carbon, but during the past twenty to twenty-five years some thousands of tons of tungsten steel have been used annually for this purpose. More recently alloys containing a high percentage of cobalt have been largely employed, notwithstanding their higher cost, following the discovery by Professor Honda, of Japan, that such material is specially suitable for permanent magnets. This cobalt steel has also been found superior to tungsten steel as a material for the permanent magnets of magnetos and other apparatus subject to powerful demagnetising influences. Its coercive force is over 200, compared with about 70 for tungsten steel and 45 for carbon steel, whilst the remanent magnetism is similar to that of tungsten steel, namely about 10,000, the figure for carbon steel being about 9,000.

Reference has already been made to the low hysteresis properties and high electrical resistance of the author's silicon steel, and to the great savings resulting from the use of this material in transformers and electrical machinery.

The extraordinary material "Permalloy," containing about 80 per cent. nickel and 20 per cent. iron, has such a remarkably high permeability at low inductions that it approaches saturation in the earth's magnetic field.

These few examples of the enormous range and variety of magnetic properties obtainable in steel by suitable alloying and correct heat treatment find a parallel in almost every other property. Notwithstanding all that has been accomplished in the field of alloy steels, there are still innumerable combinations to be made, and there appears to be no limit to the special qualities which may be imparted to steel by alloying, and therefore no limit to the further advances which improved materials may bring about in engineering, technology and, in fact, in every walk of life.

Importance of Heat Treatment

The special qualities of almost every alloy steel are directly dependent upon the application of correct heat treatment. If only the raw and untreated steel be used or if faulty heat treatment be carried out, this inevitably results in a more or less complete

sacrifice of the desirable properties of alloy steels, including also special and high carbon steels. When it is remembered that a difference of only 3° or 4° C. exists between temperatures at which carbon steel will or will not harden, it will be appreciated what care and skill are required, and how much depends on the availability of reliable pyrometers.

Long experience and much research have been needed to discover the best methods of preparation and heat treatment for special steels, and the fact that heat treatment is an essential factor in the preparation of alloy steels for service and the remarkable results thus obtained have led to an increased appreciation of the possibilities of heat treatment in connection with carbon steels. The advance in knowledge concerning alloy steels has reacted, in fact, upon the technology of carbon steels, and has led to the discovery of the fact that properly treated carbon steels are comparable with some of the more expensive alloy steels in many applications.

The work of the metallurgist during the past fifty years has benefited the engineer by providing not only new alloys, but also methods of heat treatment which enormously increase the practical value of both alloy steels and simple carbon steels.

Sheffield and the Rise of Ferrous Metallurgy

In view of the enormous extent to which the iron and steel industry of this country has contributed to our national strength and prosperity and, in fact, to the advance of civilisation throughout the world, it should never be forgotten how many of the most important developments in ferrous metallurgy have emanated from Sheffield during about the past 120 years.

Huntsman perfected his invention of crucible cast steel at Handsworth, near Sheffield. Faraday sent his alloys to be made "in the large way" at Sanderson's works. The Sheffield firm of Green, Pickslay & Co. used certain of Faraday's alloys for commercial manufactures. Robert Mushet developed his high-speed tool steel in Sheffield. The Bessemer process, which practically revolutionised the world, might have come to grief but for the aid rendered by certain prominent Sheffield steelmakers. The first large application of the Siemens open-hearth furnace was made by the Vickers Co. It was in Sheffield that the author discovered and invented the Hadfield manganese steel, silicon steel, and other alloy steels from which such great advances have followed. It was in Sheffield that Brearley developed chromium steel as regards its stainless qualities. It was Arnold of the Applied Science Department of the Sheffield University who helped greatly to develop

scientific metallurgy by his researches and his able methods of instruction. Credit for applying the microscope to the examination of minerals and extending the same method to the study of metals belongs to another citizen of Sheffield, the late Dr. Henry Clifton Sorby, F.R.S. So the tale goes on. The names of Brown, Jessop, Cammell, Firth, Sanderson, Mappin, Wostenholm, E. Reynolds, T. Vickers, Wilson, Andrew, Fox, Seebohm, Howell, Bingham, Doncaster, Hall, Allen, Senior, Osborn, Spencer, Stubbs, Balfour, Rodgers, Hoyle, Wardlow, and many others call to mind those who laid foundations on which later workers have built much of the science of metallurgy, the prosperity of Sheffield and its high position in our Empire.

Much help has been rendered regarding the supply of trained metallurgists, engineers also other assistance by the Sheffield University, chiefly from the two Faculties, Engineering and Metallurgy, in its Department of Applied Science. Interest in scientific metallurgy was largely stimulated in Sheffield by the series of Lectures delivered at the Firth College in 1883 by the well-known metallurgist the late Professor Bauerman. Then followed the establishment of the Technical School, including the Metallurgical Department, which was under Professor Greenwood from 1885 to 1889. Next to take charge of the Faculty of Metallurgy was the late Professor J. O. Arnold, F.R.S., to whose life-work full reference has already been made; the next occupant being Dr. C. H. Desch, F.R.S., who has also made many important contributions to metallurgical science.

The Vice-Chancellors of the University of Sheffield, Dr. W. M. Hicks, F.R.S., Sir Charles Eliot, Mr., now the Rt. Hon. H. A. L. Fisher, Professor W. Ripper, and Sir Henry Hadow, have rendered great service in the development of Sheffield's educational facilities, whether literary, scientific or technical. To the new Vice-Chancellor, Professor A. W. Pickard-Cambridge, every good wish is extended by the citizens of Sheffield in the carrying on of his important office the object of which is so well summed up in the motto of the University, "*Rerum cognoscere causas.*"

The important part played by Sheffield in the history of metallurgy from the time of Chaucer or earlier, down to the present day was fully set forth in the author's address when declaring open the new Engineering and Metallurgical Laboratories at the twenty-first anniversary celebrations of the Sheffield University on July 2nd, 1926.

As early as 1787 about a dozen Sheffield firms were engaged in the converting or cementation process ; also, about fifty makers

of edge tools, forty of files, 300 of pen, pocket and table knives, fifty of razors, nearly 100 of scissors, and between sixty and seventy engaged in the manufacture of scythes, sickles and shears. Many of the names of the manufacturers then engaged in the Sheffield trades are still household words, and therein lies perhaps one of the main reasons for Sheffield's eminence in metallurgy, that is this city has had the advantage of the cumulative skill and experience of generation after generation of craftsmen.

In making this statement with reference to Sheffield there is no desire to ignore or underrate the valuable work done in other parts of our Empire, also by the metallurgists of other nationalities, including those in France, the United States, Germany, Italy, Belgium, and now in the Far East by Japan. This reference to the " Island Country of the East " is fully justified and confirmed by the important metallurgical work now carried out there, also by the fact that in 1922 Professor Kotaro Honda, Director of the Japanese Institute for Iron, Steel and other Metals, of the Tohoku Imperial University, received the blue ribbon of the metallurgical world in the award to him by the Iron and Steel Institute of its Bessemer Gold Medal. By the numerous metallurgical papers issued so freely and liberally by Professor Honda and the Government Research Department at Sendai, Japan is fully doing its share in helping to advance the world's knowledge of metallurgy. Great credit is also due to this country for the striking success of the World Engineering Congress held at Tokyo two years ago.

The Field to be Explored

It cannot be emphasised too strongly that, notwithstanding the labours of many hundreds of investigators in various parts of the world during the past fifty years, and despite the marvellous alloy-steel products already employed in the many phases of our present-day civilisation, we are still much nearer the beginning than the end of the task of investigation and development. Much has been accomplished, but more remains to be done.

In his book *Metallurgy and Its Influence on Modern Progress* the author gives the following figures, which are still substantially true, though a certain number of fresh alloys have since been investigated. There are some twenty-three elements the effects of which have been fairly fully investigated as regards their influence on iron in binary alloys, that is, alloys of iron with one other element. Confining ourselves to these twenty-three elements alone, and actually there are about sixty others, the number of possible ternary alloys of two elements with iron is 253, the number of

possible quaternary alloys of three other elements with iron is 1,771. The total number of possible ternary and quaternary alloys is thus 2,024, using only the twenty-three elements mentioned, and the complete investigation of this field must occupy many years. Nor does this exhaust the possibilities of ferrous metallurgy, for there are innumerable other combinations awaiting examination.

Original work in this direction is being steadily carried on by metallurgists of all nationalities in such leisure as they can wrest from what may be termed routine problems. The latter, in themselves, are numerous and complex in a modern steelworks called upon to meet requirements of ever-increasing severity.

Importance of Research

If there is one outstanding lesson that has been brought out by the metallurgical progress of the past half-century it is the importance of continual research. There is little or no possibility of predicting results by analogy, interpolation or extrapolation. The research laboratories of the author's firm in Sheffield form a striking example of the costly and elaborate equipment required, and the high degree of training which is necessary in those carrying out the operations, in order that the chemical composition, mechanical, electrical and other physical properties of steel test pieces may be fully determined and correlated, and the best methods of dealing with the material ascertained.

It is not sufficient for the metallurgist to examine fully the properties of different compositions and then assume that a third steel, of intermediate composition, will have intermediate properties. It may have entirely different qualities of the highest industrial importance, or it may be quite useless. The only way to find out is to investigate all the properties of each particular steel concerned. Even when a steel has been discovered that fulfils necessary requirements it may cost thousands of pounds and need years of work to develop methods for making it on a commercial scale.

To-day, when the unique advantages of manganese steel are so fully recognised, and very large quantities of this material are used all over the world, it is interesting to recall the fact that its remarkable properties involved long and costly research extending over several years in order to determine how the alloy could best be worked and applied. Also, the extraordinary nature of its properties delayed for a time a full appreciation of the purposes to which the alloy could be applied.

The research worker is often faced by many difficulties after his

initial or basic success has been achieved. Sometimes he produces new materials of such remarkable properties that those who ought to use them seem to think them "too good to be true"! The practical utilisation of more than one special steel has been delayed by this attitude of mind, but the truth is that no reputable steelmaker would be so foolish as to claim more for his steels than could be upheld in service.

Half a century or so ago, when the author began his metallurgical career, facilities for research were almost non-existent. Now they are to be found on every side, and it is essential that full use should be made of them. Further than this, every opportunity should be taken of improving and adding to the facilities available. The diversity of properties obtained and demanded in the past encourages us to hope for even greater variety in future, whilst, on the other hand, it emphasises the extreme importance of investigating as completely as possible every known and new material. Properties which are of little interest to-day may be in urgent demand to-morrow, and a great opportunity may lie before the worker who can meet new requirements from his existing records.

Finally, it may be said that to-day there are but few locked-up cupboards containing secret information. No one has more freely put from time to time before the world, the results of his labours than the metallurgist.

British Photomicrographic Apparatus

In view of the great importance of the microscopic examination of the structure of steels, the author offered, some time ago, a prize for the best form of photomicrographic apparatus of British manufacture, which should embody all that experience had shown to be necessary to carry out the highest type of metallographic research in the most convenient manner. This prize was won by Messrs. R. and J. Beck, of London, and the new apparatus designed and produced by them, which at their request is known as the "Hadfield-Beck" Metallurgical Microscope and Metallographic Apparatus, is believed to be in many ways superior to equipments hitherto obtainable. The Hadfield Research Laboratory has been equipped for some time with this new apparatus, and excellent results are being obtained from it in everyday work.

Needless to say, the author has not the slightest financial interest in Messrs. Beck's firm or in the new microscope and metallographic apparatus. The matter is mentioned only to show how important it is that each one of us should do everything possible to support

home industries. Arising in the first instance from the need of the Hadfield Research Laboratory for additional equipment, this new British metallographic outfit, including British-made lenses, has been developed in many ways even superior to anything that can be obtained from abroad. There is therefore now no necessity to go outside this country, and it is gratifying that several equipments have already been ordered by a number of other large firms with equally satisfactory results. This is an interesting illustration of co-operation between the scientific research worker and the manufacturer of apparatus, which before the war was somewhat deficient.

The Future

It would be difficult to arrive at an accurate estimate of the number of workers now engaged on the scientific side of ferrous metallurgy, specially as many of those who are adding steadily to knowledge and resources in this field are normally engaged for the greater part of their time in the routine work of supplying the world's demand for vast quantities of steels of all types. It is certain, however, that of the 70,000 or more members of the principal engineering societies of the British Empire, and the 200,000 or so members of the United Engineering Society of the United States of America, to say nothing of the tens of thousands of members of engineering and allied societies in France, Germany, Italy, Belgium, Japan, Russia, and other countries, the great majority are more or less directly dependent upon the use of various types of ordinary and alloy steels in their professional work.

Faraday was the pioneer of systematic research in the field of alloy steels more than 110 years ago, and hundreds of able and experienced investigators now devote their lives to the "infinity of metallic combinations"—these are his own words—upon which he started alone. Truly, he opened a rich but vast and difficult field of research. The number of different alloys of steel now used commercially is legion, and the total weight of their production runs into millions of tons per annum. Nevertheless, the future development of alloy steels will undoubtedly be greater than any yet realised. Apart from the fact that there must still be many valuable alloys awaiting discovery in the thousands of possible combinations of different alloying elements, both of the ferrous and non-ferrous types, the uses of known alloys will go on increasing as engineers and others impose higher and higher requirements in the way of strength, lightness, resistance to corrosion, and other

special qualities. In this there is no cause for despondency or discouragement, but rather for hope and inspiration. The future of such steels is of incalculable extent and importance, and no doubt the younger men will see to it that the position of this country in regard to alloy steel development is fully maintained.

CHAPTER X

CONCLUSION

THE fascination of scientific research work is cumulative in effect. In almost every instance the discovery of one fact leads to fresh problems, the scope of the inquiry widens rapidly and the results attained are often greater and more numerous than were originally anticipated. This has certainly been the case as regards the author's investigation and research on Faraday's "Steel and Alloys."

The author was originally led to undertake this research by the consideration that chemical analyses, physical, mechanical and other tests on Faraday's specimens would furnish definite information, hitherto lacking, concerning their composition and properties. Apart from the general desirability of obtaining the information and presenting this publicly, it was felt that amongst others this research would be of special interest to the Royal Institution, the Royal Society, and in connection with the Faraday Centenary Exhibition held at the Royal Albert Hall from September 23rd to October 3rd, 1931. The seventy-nine specimens of Faraday's "Steel and Alloys" from the Royal Institution, also the further batch of ten specimens from the Science Museum described later, making eighty-nine in all, were exhibited in one of the sections, namely "E," sub-section "E–4," surrounding the Central Stand "A," upon which stood the statue of Michael Faraday and his personal mementoes. These specimens were actually made in the laboratory of the Royal Institution, being kept there for more than a century, and it was to that body that Stodart and Faraday presented their first paper on alloys of steel in 1820; while their second paper was presented to the Royal Society in 1822. Each of these bodies has thus a direct connection with the historic specimens, and as anticipated the Members and Fellows of each of them have shown special interest in the results of the research described and presented in this book. As regards the memorable Celebrations held from September 21st to 25th in honour of Faraday at the Royal Institution, also the great Exhibition at the Royal Albert Hall in commemoration of the Centenary of Faraday's discovery of the principle of electro-magnetic induction, it seemed

specially appropriate that the fullest possible information, including the exhibit of the eighty-nine steel specimens themselves, concerning Faraday's work on "Steel and Alloys," should be made available alongside the exhibits of his electrical, chemical and other discoveries and many other exhibits, as well as examples of the marvellous and world-wide results that have sprung from them.

Though the author realised at once the interest attached to determining, for the first time, the chemical composition and other properties of Faraday's specimens of steel and alloys, he did not foresee the full amount of work that would be involved and the extent and significance of the information that would be obtained. The author felt, however, that the permission granted to him by the Royal Institution to subject the specimens to the fullest possible investigation placed upon him the responsibility to give as complete an account as possible of Faraday's labours in this field and the results which attended them. The research has been a labour of love to all concerned, and it is hoped that the extent of the information thus brought to light will prove to be of considerable value and benefit.

At a very early stage the author realised that the importance of Faraday's work in this field of metallurgy had hitherto been under-estimated, and as the research proceeded he became still more strongly convinced of this.

In his *Historia et Origo Calculi Differentalis* (1676), Leibniz says:—

> "It is an extremely useful thing to have knowledge of the true origins of memorable discoveries, especially those that have been found not by accident but by dint of meditation. It is not so much that thereby history may attribute to each man his own discoveries and others should be encouraged to earn like commendation, as that the art of making discoveries should be extended by considering noteworthy examples of it."

These words appear to be specially applicable to Faraday's research, also to the present research on his specimens of steel and alloys.

The author feels that the time and labour that have been expended upon the examination of Faraday's specimens by modern methods of chemical, physical, metallographic and other research have been fully justified by the remarkably interesting results obtained, and now published for general information. Also, he feels that an enquiry of this kind must produce facts of present or future scientific value, quite apart from the general interest in the elucidation of new information about the materials

with which Faraday worked. It is hoped that the results of the present investigation may be regarded as a contribution to the history of science and scientific method, and, above all, as an appropriate and worthy tribute to Faraday's memory and the value of his metallurgical work.

Undoubtedly, Faraday foresaw the possibility of alloy steels having specially valuable properties, though neither he nor anyone else at that time could possibly have imagined the indispensable part that such materials would play in the civilisation of to-day. Without alloy steel, many of the amenities, conveniences and even necessities of present-day existence would be physically impossible. The same may be said of the services rendered to civilisation by electrical engineering. Faraday may truly be said to have unbarred the gates in both of these fields. It was in 1821 that he discovered the principle of the electric motor, and it was another ten years before he discovered the equally important principle of magnetic electric induction. Also, as Professor Silvanus P. Thompson once said: "Even the keenest of intellects had not in 1857 grasped the real significance of the dynamo, in fact it was not until 1865–1875 that these principles were made use of practically." This was about half a century after Faraday's discovery of 1821. Nevertheless, Faraday is always regarded, and rightly so, as the Father of the Electrical Industry. In the same way, the author maintains that Faraday may justly be regarded as the pioneer of alloy steels, for he was the first to conduct systematic researches in this field, and he achieved a remarkable degree of success. As shown by the present research, he was, in fact, far in advance of his time both in the conception and in the results arising out of these researches.

The engineer may plan and design, the chemist and physicist may examine and determine the composition and properties, but it is largely to those who are engaged in the study of the science of metallurgy with its many branches that the modern world owes its progress. Take away ferrous alloys and not only would progress be hindered, but, in many respects, we should be thrown back to the conditions of a century ago. While it is true that demand generally induces supply—and lack of demand was one of the main reasons why there was no immediate and general development of Faraday's work on "steel and alloys"—yet the wonderful world progress of the past fifty years has undoubtedly been brought about by metallurgical developments, largely in the field of alloy steels.

In a recent interesting article entitled "History," by that able

contributor Mr. J. R. Hewett, appearing in the *General Electric Review* (U.S.A.), he makes the suggestion that " if Faraday arose to-day he would tell us that he was inspired by Davy, Volta, Galvani, Gilbert, and many others who prepared the way for his own great discoveries. Every great name of the past, in the many varying walks of life, that has shone forth as a bright star on a dark night to illuminate the vista of the past, has depended upon the dark background to bring forth its brilliance. If Faraday were to walk through modern electrical factories, he would marvel more at what has been done since his day than in his day and before him. He would acknowledge that it was those who followed and turned the fruits of his discoveries to the service of mankind that have made his name immortal. The lustre of his fame depends on no particular date or event, but on the background and foreground that have brought forth his works in high relief."

So in the field of alloys of steel, Faraday's work stands out brightly on the dark background of an almost complete absence of any previous knowledge concerning this subject. His alloys may appear humble and imperfect beside the efforts and productions of to-day, and he would undoubtedly marvel at all that has been accomplished since he worked with his little " blast furnace," but let us not forget that in this field, too, his fame stands out in high relief between the background of the eighteenth century and the foreground of the twentieth.

Long acknowledged as a leading chemist and as the founder of the electrical industry, Faraday is now seen to have been a metallurgical investigator of great ability and brilliant inspiration. The author is gratified that he has had the privilege of proving this by interpreting evidence provided by Faraday himself and held fast for more than a century in the heart of a few pounds of steel.

APPENDIX I

SERIATIM LIST OF PAPERS, BOOKS AND SPECIAL LETTERS CHIEFLY RELATING TO METALLURGICAL MATTERS BY

(*a*) MICHAEL FARADAY: 1791–1867 (76); elected F.R.S., 1824.
(*b*) JAMES STODART: 1760–1823 (63); elected F.R.S., 1821.
(*c*) FARADAY and STODART jointly.

The author has been unable to discover any papers by Stodart during 1805–1820, that is, between his paper on the Precipitation of Platina and the first of his two papers jointly with Faraday on "Steel and Alloys."

Year.	Name.	Title of Paper.	Where appeared.
1802	Stodart	On the Effects of Respiration of the Nitrous Oxide.	*Nicholson Jnl.*, I., 225/7.
1804	Stodart	Account of an Experiment to Imitate the Damascus Sword Blades.	*Nicholson Jnl.*, VII., 231/2.
1805	Stodart	Method of Gilding upon Steel by Immersion in a Liquid.	*Nicholson Jnl.*, XI., 215/6.
1805	Stodart	Precipitation of Platina as a Covering or Defence to Polished Steel, and also to Brass.	*Nicholson Jnl.*, XI., 117/9.
1816	Faraday	Analysis of the Native Caustic Lime of Tuscany.	*Q.J.S.*, Vol. I., 260/1.
1819	Faraday	Separation of Manganese from Iron.	*Q.J.S.*, Vol. VI., 357/8.
1819	Faraday	An Analysis of Wootz or Indian Steel	*Q.J.S.*, Vol. VII., 288/290.
1820	Faraday and Stodart	Experiments on the Alloys of Steel made with a view to Its Improvement.	*Q.J.S.*, Vol. IX., 319/330. Tilloch, *Phil. Mag.*, Vol. LVI., 1820, pp. 26-35. *Phil. Mag.*, Vol. LX., July-Aug., 1822, 355.
1820	Faraday	*Letter (April 20th) to de La Rive regarding experiments.	*R.S. Proc.*, XVII., 1868–9.
1820	Faraday	*Letter (June 26th) to de La Rive sending Abstracts of Paper on Steel.	Bibl. Univ., Geneva, XIV., 1820, pp. 209–215.
1821	Faraday	*Love Letter to Miss Sarah Barnard in which steel is mentioned.	*Life of Faraday.* Dr. Bence Jones, F.R.S., Vol. I., p. 283.
1822	Faraday and Stodart	On the Alloys of Steel.	*Phil. Trans.*, 21-3-1822, p. 252. *Phil. Mag.*, Vol. LX., July-Aug., 1822, p. 363.
1827 1830 1832	Faraday	†*Chemical Manipulation.*	Book.

* = Letters.
† = Books.

Seriatim List of Papers, etc.—*continued.*

Year.	Name.	Title of Paper.	Where appeared.
1836	Faraday	‡On the General Magnetic Relations and Characters of the Metals.	*Phil. Mag.*, Vol. VIII.
1845	Faraday	‡On the Magnetic Relations and Characters of the Mëtals.	*Phil. Mag.*, Vol. XXVII.
1849	Faraday	*Letter to Percy.	*Life of Faraday.* Dr. Bence Jones, F.R.S., Vol. II., p. 250.
1857	Faraday	*Letter to Percy.	*Life of Faraday.* Dr. Bence Jones, F.R.S., Vol. II., p. 395.
1861	Faraday	‡On Platinum.	*R.I.Proc.*, Vol. III.
1859	Faraday	†*Experimental Researches in Chemistry and Physics.*	Book
1863	Faraday	*Letter to Percy. ("Cannot call to mind where specimens are.")	*Life of Faraday.* Dr. Bence Jones, F.R.S., Vol. II., p. 461.

* = Letters.
† = Books.
‡ These appear to be the only subsequent papers relating to Metallurgy between the years 1822 (Faraday was then 31 years of age) and 1867 (76 years of age), that is, in 45 years. They have no relation to "Alloys of Steel" or Ferrous Metallurgy, with which alone the author is dealing in this book.

APPENDIX II

Physical Constants of the Elements employed by Faraday in his Experiments on "Steel and Alloy" in order decreasing of their Melting Point in each Group.

Element.	Chemical Symbol.	Atomic Number.	Atomic Weight.	Melting Point °C.	Specific Gravity.	Specific Heat.	Brinell Hardness.	Coefficient of Expansion. Millionths per °C.	Thermal Conductivity. C.G.S. Units.	Specific Electrical Resistance. Microhms per C.C.
A.—Iron.										
Iron	Fe	26	55·8	1532	7·86	0·107	97	11·7	0·148	10·0
B.—Noble Metals.										
Osmium	Os	76	190·8	2700	22·48	0·031	—	6·1	—	9·0
Iridium	Ir	77	193·1	2350	22·40	0·031	217	6·5	0·141	6·0
Rhodium	Rh	45	102·9	1955	12·50	—	156	8·4	0·213	5·1
Platinum	Pt	78	195·2	1763	21·45	0·032	44·3	8·9	0·166	10·5
Palladium	Pd	46	106·7	1555	12·00	0·059	61	11·8	0·161	10·8
Gold	Au	79	197·2	1063	19·30	0·031	33	14·2	0·705	2·4
Silver	Ag	47	107·9	960·5	10·50	0·056	37	18·9	1·000	1·62
C.—Other Metals.										
Titanium	Ti	22	47·9	1800	4·50	0·145	—	—	—	3·0
Chromium	Cr	24	52·0	1615	7·10	0·106	91	8·2	—	2·6
Nickel	Ni	28	58·7	1455	8·90	0·105	144	12·8	0·140	6·9
Copper	Cu	29	63·6	1083	8·92	0·092	53	16·6	0·927	1·69
Tin (White)	Sn	50	118·7	231·8	7·31	0·054	15·6	20·0	0·156	11·4
D.—Non-Metals.										
Carbon: (*a*) Amorphous	C	6	12·0	—	3·51	0·122	—	0·9	0·0082	5×10^{20}
(*b*) Graphite	C	6	—	3500	2·55	0·169	—	3·0	0·0374	1,400
Silicon	Si	14	28·1	1420	2·40	0·176	240	2·8–7·3	—	85,000
Sulphur (Rhombic or Orthorhombic)	S	16	32·1	112·8	2·07	0·172	36	64	—	2×10^{23}

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